Misan Journal of Engineering Sciences ISSN: 2957-4250
Vol. 5, No. 1, 28 June 2026 ISSN-E: 2957-4242

Reliable Propagation Model for Satellite Communication over Iraqi Regions

Taghreed A. Noori[1]* and Hasanain A. H. Al-Behadili[1]

[1] *Department of Electrical Engineering, College of Engineering, University of Misan, Amarah, Iraq.*
*Corresponding author E-mail: enghs2306@uomisan.edu.iq

(Received 20 Dec 2025, Revised 23 March 2026, Accepted 3 April 2026)

Abstract: Satellite communication systems are an important part of the worldwide telecommunication systems especially in areas where terrestrial infrastructure is limited or unreliable. Their performance is highly dependent on the accuracy of models for the propagation of radio waves, which have to account for the effects of the atmosphere such as rain, humidity, airborne dust. This paper shows a comprehensive review and analytical analysis of the satellite signal propagation over Iraqi regions by taking into consideration the unique climatic conditions of this country that are associated with the existence of frequent dust storms, high humidity for a long time in southern regions and seasonal rainfalls in northern areas. The results of the review demonstrate that the accuracy of widely used international propagation models such as ITU-R P.618, Crane and Longley-Rice can be reduced when applied directly to the dust dominant and spatially heterogeneous environment of Iraq mainly because of the lack of local calibration and the representation of the attenuation related to aerosols. Global, regional and Iraqi studies are systematically analysed to assess physical, empirical and hybrid strategies of the propagation to reveal critical gaps of long-term measurements, spatial coverage and standardized modelling practices. Based on these findings, a conceptual hybrid framework which is called the AI-Based Iraqi Propagation Model (AI-IPM) is proposed. The framework combines the use of ITU-R physical formulations with machine learning techniques to adaptively predict the attenuation based on the indicators of meteorological conditions and the link quality. While enhanced robustness is a feature that is anticipated for dust- and humidity-dominated conditions, large-scale validation for across the country scale necessitates the use of standardised long-term propagation data sets. The paper concludes with recommendations of the need for a national Iraqi propagation database to aid reliable planning of satellite communications, especially where Ka-band and Q/V-band systems are concerned.

Keywords: Satellite communication, propagation modeling, atmospheric attenuation, Iraqi climate, artificial intelligence.

1. Introduction

Satellite communications are one of the bedrocks of modern telecommunication infrastructures, they are the main means of data and information transmission in regions where terrestrial networks are hard or impossible to install [1]. These systems are now embedded in the global services including broadband Internet, aeronautical and maritime navigation, meteorological monitoring, defense operations, distance education and international broadcasting [2]. Over the past two decades the rapid development of satellite technology has led to a high level of dependence on satellite communication systems by developing countries - including Iraq, the growth of high frequency bands such as Ku-band and Ka-band has allowed for the higher data transmission rates as these bands are more sensitive to environmental and atmospheric factors [3]. A satellite communication link works on the principle of transmitting a signal from an Earth station to a satellite in space via uplink, and then retransmitting it back to another Earth station via downlink [4]. The quality of the received signal depends on a number of factors including distance between the satellite and the Earth station, elevation angle, frequency band used, and characteristics of the medium through which the electromagnetic wave is propagated - mostly the atmosphere including clouds, water vapor, and dust particles [5].

DOI: https://doi.org/10.61263/mjes.v5i1.249

This work is licensed under a Creative Commons Attribution 4.0 International License.

Under ideal conditions the Free Space Path Loss (FSPL) model can be used to estimate transmission losses, however, in complex environments such as Iraq, the signal is subject to degradation caused by multiple factors such as humidity, rain and dust storm [6].

.

These phenomena cause attenuation, which results in a reduction of signal power, in a decrease of Carrier-to-Noise Ratio (C/N) and in an increase of Bit Error Rate (BER), thus reducing communication reliability [7].

1.1 Significance of Propagation Studies

Propagation modeling is the foundation for design and optimization of satellite communications systems. It determines the relationship between the transmitted and received power and aids in link budget analysis and to estimate the signal losses due to atmospheric conditions [8]. In arid and semi-arid climates such as Iraq, the propagation behavior is so different from that of tropical or polar climates [9]. However, studies have shown that dust storms can cause attenuation in the Ka-band from 6-10dB/km under severe conditions [10]. In contrast, high humidity levels in the south of Iraq (e.g. Basra and Maysan) cause an increase in the microwave absorption, especially for frequencies above 10 GHz [11].

1.2 Climatic Features of the Iraqi Environment

Iraq's climate has an extreme spatial contrast - from the arid desert climate in the west and south to semi-humid in the northeast [12]. Meteorological reports and the observations of the US National Aeronautics and Space Administration (NASA) satellites show that Iraq has partial days of dust presence (272 days in a year) and full dust storms (around 100 days) with the highest dust pollution in Al-Anbar, Salahuddin, and Dhi Qar [13]. According to Albarakat & Lakshmi [14], based on the usage of the satellite imagery from the Moderate Resolution Imaging Spectral Radiometer (MODIS), in July 2009 a h uge dust storm covered more than 75% of Iraq, and dropped the horizontal visibility in Baghdad to less th an 200 meters [15]. In the figure below (a) Massive dust storm over most of Iraq on 3 July 2009 - this true color satellite image displays a thick dust between Syria and the Iraq-Iran border; (b) 4 July 2009 - the dust storm has spread towards the east and southeast, over Iran and the Ar abian Gulf; (c, d) 5-7 July 2009 - consecutive satellite images show the dust storm has continue d to spread towards the east and southeast, covering most of Iran west of the Caspian Sea, Ku wait and the Arabian Gulf. (e) 31 July 2009 - the same dust storm spread over eastern Iran, Ku wait, Pahraein, Qatar, the Arabian-Persian Gulf, the United Arab Emirates and Oman [15].

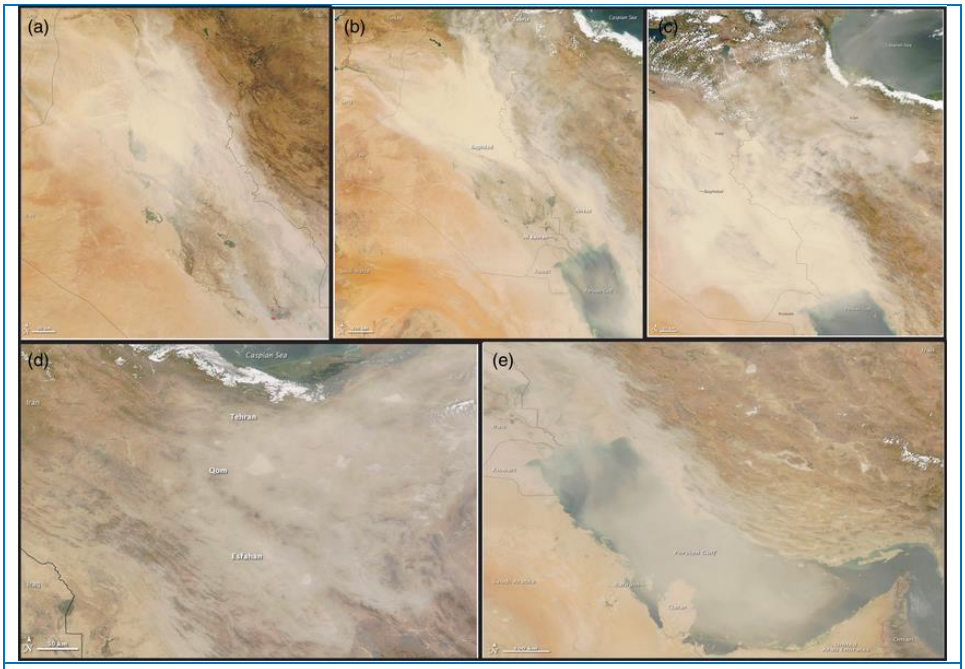


Fig. 1 July 2009 Dust Storm Over Iraq (MODIS Imagery) [15]

Moreover, high humidity in the southern parts and seasonal rainfall in the north impact the attenuation, particularly in Ku and Ka frequencies, where rain rates more than 25 mm/hr cause high signal loss, this is in agreement with the ITU-R P.618-13 recommendation on rain attenuation [16].

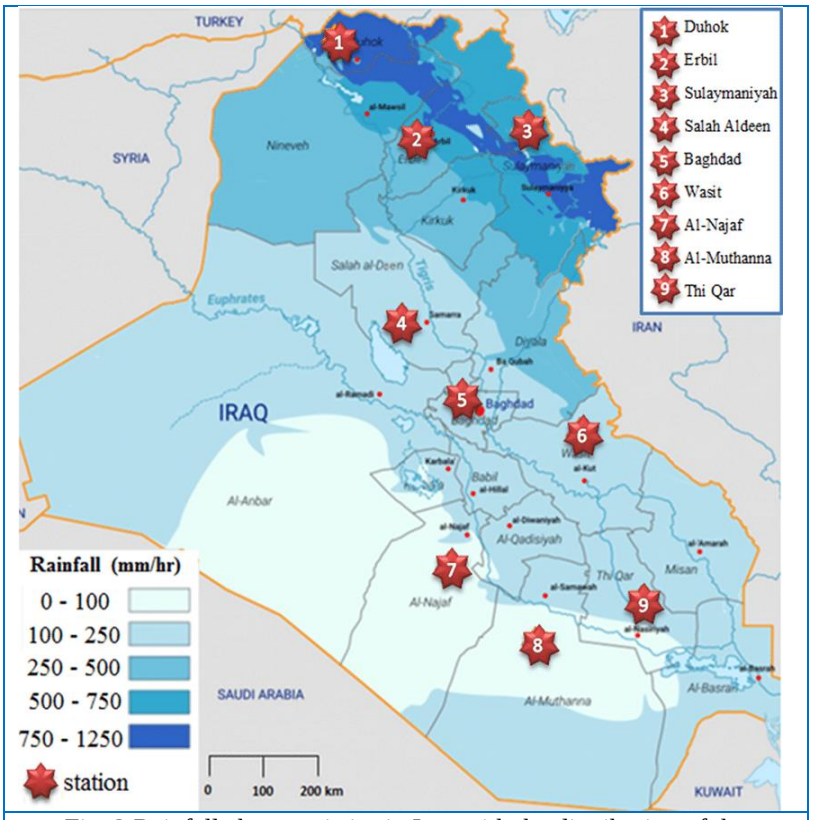


Fig. 2 Rainfall characteristics in Iraq with the distribution of the measurement stations [16]

As a result, the atmospheric conditions in Iraq, which are a combination of dust, humidity, fog and precipitation, produce one of the most difficult environments in the world for accurate propagation modeling [17].

1.3 Research Problem and Objectives

Despite efforts that have been made to develop various international propagation models (e.g., ITU-R, Crane, Hata, Longley-Rice), most of these models were developed for climates which are significantly different from that of Iraq. They are based on empirical datasets which do not accurately reflect the unique combination of dust density, low rainfall and variable humidity in Iraq. Thus, there is a pressing need for a sound and localized calibration model designed for the Iraqi environment - one capable of effectively considering the impact of dust storms, rainfalls and humidity in the C, Ku and Ka bands. Such a model would lead to better Quality of Service (QoS), reduce interruptions on the link, and increase national satellite communication reliability.

1.4 Objectives of This Review

This review aims to:

1. Present and analyze some major global propagation models used in satellite communication system.
2. Evaluate their use in Iraqi climatic and environmental conditions.
3. Identify the research gaps in local research related to the effects and influences of dust, rain and humidity on satellite signal propagation.
4. Propose future directions for development of a localized model using Iraqi meteorological data for attenuation prediction and artificial intelligence (AI)
5.

2. Theoretical Background of Satellite Communication

2.1 General Overview

Satellite communication systems represent one of the most complex and multidisciplinary branches of modern telecommunications bringing together electrical engineering with wireless communication, atmospheric physics and orbital mechanics [18]. Despite their conceptual simplicity - having to transmit electromagnetic waves from one ground station to another via a satellite - their practical implementation involves advanced signal processing, high-precision equipment and detailed modeling of the atmosphere [19]. A typical satellite communication system has three major components:

- Earth Station Transmitter.
- Satellite Transponder.
- Earth Station Receiver.

The atmosphere of the earth is both a transmission media for waves and a major contributor to the degradation of signals by absorption, scattering, reflection, and refraction of electromagnetic waves [20].

2.2 Working Principle of Satellite Communication Systems

The signal is sent from the ground station to the satellite in orbit through the uplink usually in the frequency bands 5.9-6.4 GHz (C-band) or 14-14.5 GHz (Ku-band), after being received by the satellite transponder, the frequency is down-converted to prevent interference and retransmitted back to earth via the downlink, usually working at 3.7-4.2 GHz (C-band) and 10.95-12.75 GHz (Ku-band) [21]. The basic performance for the satellite link is calculated using the following Equation, known as the Link Budget Equation:

$$P_r = P_t + G_t + G_r - L_p - L_{atm} - L_{rain} - L_{misc} \quad (1)$$

where:

(P_r): Received power (dB), (P_t): Transmitted power (dB), (G_t, G_r): Antenna gains of the transmitter and receiver (dB), (L_p): Free Space Path Loss (dB), (L_{atm}): Atmospheric loss (dB), (L_{rain}): Rain attenuation (dB), (L_{misc}): Miscellaneous losses such as connector and reflection losses [22]. This equation is the key to the development of satellite links, the basis for signal reliability and systems optimization.

2.3 Frequency Bands of Satellite Communications

Frequency bands are a very critical part of the quality, capacity, and reliability of satellite communication systems. The most common bands are summarized due below:

Table 1 Frequency Bands of Satellite Communications

Frequency Band	Range (GHz)	Typical Applications	Advantages	Limitations
L-band	1–2	GPS, maritime communication	High resistance to rain and dust	Limited bandwidth
C-band	3.7–6.4	Broadcasting, governmental links	Stable under weather variations	Requires large antennas
Ku-band	10.7–14.5	VSAT, satellite Internet	High data rate, compact antennas	Sensitive to rainfall
Ka-band	17.7–31	Next-generation broadband systems	Very high spectral efficiency	Very high attenuation in rain and humidity

Studies have shown that Ka-band offers better spectral efficiency than Ku-band at the expense of much higher atmospheric vulnerability [23].

2.4 Selection of Frequency and Signal Loses

The Free Space Path Loss varies with both frequency and distance in a proportional manner and is defined as:

$$FSPL(db) = 92.45 + 20\ \log_{10}(f) + 20\log_{10}(d) \qquad (2)$$

where (d) is the distance in kilometers and (f) is the frequency in GHz [24]. For example at 38,000 km an FSPL of about 195 dB is obtained for C-band whereas for Ka-band, the loss is more than 210 dB, this brings to light the need for high power amplifiers (HPAs) and high gain antennas for modern systems to have reliable link margins [25].

2.5 Free Space and Atmospheric Propagation Models

The simplest model to determine the propagation loss in satellite systems is the Free Space Path Loss (FSPL) model, provided that no obstructions or atmospheric disturbances that affect the propagation are assumed, however, in actual Iraqi conditions this assumption breaks down due to the presence of dust particles, rain and high humidity in the air [26]. Therefore, more complex and accurate models are used:

- ITU-R Attenuation Models: account for rain and cloud losses.
- Dust and Sandstorm Models: simulate dust and aerosol-induced attenuation.
- Fog and Cloud Attenuation (ITU-R P.840): for absorption due to dense humidity and fog.

Field measurements taken in Baghdad and Nasiriyah showed that a reduction in signal strength from 0.5 dB/km to 2 dB/km was possible in normal conditions and up to 6 dB/km during severe storms [27].

2.6 Practical Application of Satellite Communication in Iraq

Iraq satellite communication covers various industries such as:

1. Civil Communications Satellite Internet (VSAT), broadcasting (Nilesat, Arabsat) [28].
2. Defense and Security: Secure X-band links for military and government [29].
3. Meteorological Monitoring: Systems such as Meteosat and NOAA GOES offer dust and cloud tracking [30].

4. Remote Sensing: Environmental and agricultural monitoring with the help of the remote sensing satellites known as MODIS and Sentinel [31].

Satellite communication systems are integrated systems, and rely on a deep understanding of the electromagnetic propagation through the earth's atmosphere, the Iraqi environment with severe dust activity, variable humidity and occasional rainfall creates special challenges for the maintenance of signal integrity. The shift to higher frequencies (Ka and Q/V bands) requires the development of a localized and calibrated propagation which represents these climatic dynamics [32].

3. Propagation Models

Propagation models are mathematical or empirical models that characterize the propagation of electromagnetic waves through the atmosphere and interaction with different environmental factors such as gases, rain, fog and dust, these models are crucial to link budget analysis, network design and performance prediction in both terrestrial and satellite systems [33]. Since the earth's atmosphere is non-homogeneous, propagation behaviour is highly dependent on the climatic and geographical conditions at the locality. For countries such as Iraq that experience severe dust activity and large spatial temperature gradients, standard global models require a lot of adaptation [34].

3.1 Free Space Path Loss (FSPL) Model

The Free Space Path Loss Model is the most basic model for propagation and is the basis for any others, it makes assumptions about an ideal environment. propagation through vacuum or clear air with no interference from the atmosphere. The equation for this is written mathematically as mentioned in equation (1). This model gives a 1st order estimation for the received power in line-of-sight (LoS) condition, but it does not consider the effect of any attenuation caused by real atmospheric conditions such as Rain fade and Dust absorption [35].

3.2 ITU-R Models

The International Telecommunication Union (ITU-R) has specified a set of worldwide agreed propagation models that account for various types of atmospheric losses as follows:

3.2.1 ITU-R P.618-13 (Rain Attenuation)

This model gives an empirical approach for predicting the signal attenuation by rainfall in the Earth-space links. It is based on the rain rate (mm/h) exceeded during a time of 0.01% and the frequency used [36].

$$A = R\gamma + eff(L) \qquad (3)$$

where (A) is the total attenuation (dB), (R) is the specific attenuation (dB/km) and (eff(L)) is the effective path length through the rain medium. In the tropical or humid areas, the attenuation value can reach up to 15 to 25 dB in Ku-band, and more than 40 dB in Ka-band during the heavy storms [37]. In contrast, in Iraq, rain attenuation is seasonal - being concentrated particularly between November and March especially in the northern governorates of Mosul and Kirkuk [38].

3.2.2 ITU-R P.840-8 (Attenuation in the Cloud and Fog)

This model derives the estimate of attenuation because of clouds and fog from the liquid water content (LWC) and the effective temperature of the cloud layer, at 20 GHz the attenuation can be 1-3 dB/km under dense fog conditions, for southern Iraq with the humidity often over 80% this is an important effect during winter months [39].

3.2.3 ITU-R P.837-7 (Rainfall Rate Maps)

This recommendation presents rainfall statistics needed in P.618 calculations that provide global rainfall rate contours for various exceedance probabilities, however, these maps underrepresent the desert areas of Iraq where data on rainfall is minimal - a drawback when upsetting the application of the ITU-R models directly [40].

3.3 Crane Global Model

Developed by Crane (1980) this model improves on the ITU predictions by incorporating regional climatic modifications to account for attenuation by rain and atmosphere gasses [41]. The model presents empirical correction factors for rain-cell size and path reduction ratio, so as to be more adaptable for semi-arid climates, however, its performance decreases where there is a high dust density or low frequency of rainfall - typical conditions of Iraq - since this technology does not account for the absorption and scattering of dust particles [42].

3.4 Dust and Sandstorm Models

In desert and semi-arid areas, dust storms are a dominant source of attenuation, especially at frequencies above 10 GHz, dust particles interact with electromagnetic waves by Mie scattering which results in both absorption and phase distortion [43]. The simplified empirical model of the attenuation of dust is given by:

$$\alpha_d = kM_d f^n \qquad (4)$$

where:

- (α): Specific dust attenuation (dB/km).
- (M_d): Dust concentration (g/m³).
- (f): Frequency (GHz).
- (k, n): Empirical constants on the basis of measuring campaigns [44].

Experimental data obtained from Baghdad and Basra indicate that the attenuation rises almost linearly with both the dust density and the frequency. At Ka-band (30 GHz) attenuation may be greater than 8 dB/km under extreme sandstorm conditions which may cause link outage of more than 40 minutes in extreme cases [45],[46].

3.5 Longley-Rice Model (Irregular terrain Model)

Although developed for terrestrial applications, Longley-Rice Model (L-R) has been modified for satellite communications in low elevation applications [47]. It uses deterministic line of sight prediction in conjunction with statistical diffraction and scattering models. In the desert areas of western Iraq, where there are some surface irregularities, which cause a partial diffraction, this model can yield an accuracy of 10-15% higher than FSPL alone [48]. The model gives median attenuation as:

$$A_{LR} = A_{LOS} + A_{diff} + A_{scatter} \qquad (5)$$

where (A_{LOS}) is the free space loss and (A_{diff}) is the losses due to diffraction and ($A_{scatter}$) is the losses due to tropospheric scattering [49].

3.6 Composite and Hybrid Propagation Model

Recent research has aimed at incorporating multiple effects rain, cloud, fog and dust into composite models and these models perform a weighted factor or machine learning (ML) algorithm-based dynamic model to predict the total attenuation [50]. One example is the Hybrid Propagation Model proposed by some recent researchers, which utilizes the combination of ITU-R base equations and locally measured data of dust concentration and meteorological parameters [51]. This hybridization increases the prediction accuracy up to 25% compared with traditional ITU-R models upon validation with VSAT performance data.

3.7 Comparative Evaluation of Models

Table 2 Comparative Evaluation of Models

Model	Major Parameter	Strength	Limitation	Suitability for Iraq
FSPL	Distance and frequency	Simplicity	Ignores environment	Poor
ITU-R P.618	Rain rate	Global standard	Weak dust correlation	Moderate
Crane	Regional rain profile	Better than ITU in rain	No dust handling	Moderate
Dust Model	Dust density and frequency	Strong in desert	Ignores rainfall	Good
Longley–Rice	Terrain profile	Useful for low elevation	Needs calibration	Fair
Hybrid	All ai-assisted	Integrates local data	Complex computation	Excellent

The table illustrates that the hybrid particularly climatic composition despite the general standard models requires a hybrid approach - one that combines ITU-R parameters with local meteorological data and artificial intelligence (AI) based regression methods.

4. Climatic Effect on Propagation over Iraq

The Iraqi atmosphere poses a special and difficult environmental scenario with considerable environmental conditions which have a severe effect on the propagation of electromagnetic waves in the communication systems by satellites, unlike tropical or temperate areas, Iraq has low annual rainfall, high dust concentration and large seasonal temperature changes that together cause distinctive propagation impairment [52]. This section describes the most important climatic factors affecting propagation in Iraq. dust storms, humidity, rain and temperature variations, based on meteorological data available from local sources and experimental measurements.

4.1 Dust Storms and Aerosols Concentration

Dust storm is the main environmental phenomenon that affects radio and satellite communication in Iraq. They are numerous, intense and spatially large, especially during the months of April to September and are propelled by the Shamal winds, which transport large masses of sand and dust from the Syrian and Arabian deserts [53]. According to the Iraqi Meteorological Organization (IMO) the frequency of dust storms is between 80 and 120 per year over Iraq with concentrations above 5 g/m^3 during the severe storms [54]. The high concentration of suspended particles increases scattering, absorption and depolarization of microwave signals especially in Ku and Ka bands [55]. Empirical researches conducted in Baghdad and Karbala have found that the attenuation by dust storm can reach 6 - 8 dB/km at 22 GHz, and even up to 10 - 12 dB/km in dense storm at 30 GHz [56]. This attenuation is mainly due to Mie scattering which takes over when the particle size is on the same order of magnitude as the wavelength of the transmitted signal. The mathematical expression for the attenuation of dust particles is given as:

$$\alpha_d = K_d C_d f^{dn} \qquad (6)$$

Where (α) is specific dust attenuation (dB/km) and (C_d) is concentration of particles (g/m^3) and (f) is frequency (GHz), (k_d) and (nd) are empirically derived constants that are dependent on the composition of the dust and the size of the grains. Satellite imagery analysis from the US based Space Observatory Satellite (NASA, MODIS) and US National Oceanic and Atmospheric Administration (NOAA, GOES) confirm that during peak summer months the dust aerosol optical depth (AOD) values over Iraq (>1.5) are extremely dense [57].

4.2 Humidity and the effect of Water Vapor

Humidity is an important factor in signal attenuation due to the absorption by gases in the air and the formation of clouds. Water vapor molecules have strong resonant frequency at 22.235 GHz and 183.31 GHz, causing strong attenuation at higher frequencies above 10 GHz [58]. In southern Iraq, particularly in Basra and Maysan the relative humidity is frequently above 80% in summer months which results in increased absorption losses [59]. The specific gaseous attenuation may be defined by the ITU-R P.676-12 as:

$$\gamma_g = (T, e, P, f) \quad N"f0.1820 \qquad (7)$$

Where (Y_g) is specific gaseous attenuation (dB/km) and (f) is frequency (GHz), (N") is imaginary part of the refractivity, (P) is total air pressure (hP_a), (e) is water vapor pressure (hP_a), (T) is absolute temperature (K). Measurements taken throughout Baghdad, Basra and Erbil indicate that gaseous attenuation is usually between 0.2 - 0.6 dB/km for Ku-band and 1 - 2.5 dB/km for Ka-band links [60].

4.3 Rain Attenuation

Although Iraq is an overall arid country, rainfall is seasonal in the northern and northeastern parts of the country (Mosul, Kirkuk, Sulaymaniyah) and less frequent in the central and southern areas [61]. Rain-induced attenuation is mainly related to the frequency above 10 GHz and its degree depends on rain rate (R) and drop size distribution (DSD). Using ITU-R P.838-3, it is possible to express specific rain attenuation as:

$$\gamma_r = kR^{\alpha} \qquad (8)$$

In which (k) and (alpha) are frequency dependent regression coefficients. For Ka-band (30 GHz), typical values are (k = 0.12), (alpha = 1.0) and for Ku-band (14 GHz), (k = 0.05), (alpha = 0.9) [62]. Field data from Erbil (2023) show that a high rainfall rate of more than 25 mm/h can cause 8-15 dB/km attenuation at Ka-band. Although the frequency of occurrence of these conditions is less than 1% per year, their effect on link availability can be critical for high-frequency satellite services [63].

4.4 Temperature and Refractive Index Spatial Variations

Temperature changes influence the refractive index (n) of the air that results in changes in the propagation path of the waves and leads to refraction and ducting effects. The refractivity (N) is given by:

$$N = (n-1) \times 10^6 = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \qquad (9)$$

where (P) and (e) are air and water vapor pressures respectively and (T) is the temperature in Kelvin [64]. In the summer the temperature at ground level in southern Iraq can be well over 50 degC, although the upper layers of the atmosphere can be much cooler and this vertical difference in temperature causes super-refraction conditions that may distort or bend microwave paths and cause fading or unexpected link gain [65].

4.5 Total Climatic Influence

In practice propagation impairment is the cumulative effect of several mass atmospheric effects (dust, humidity, rain and refractivity) acting together at the same time. A simplified combined attenuation model can be expressed as:

$$A_{total} = A_{dust} + A_{rain} + A_{gas} + A_{cloud} + A_{misc} \qquad (10)$$

This is an equation that describes the total loss in the signal adapted based on cumulative attenuation models described in ITU-R and Al-Furaiji. Simulations based on the data sets of the MATLAB and ITU-R

indicate during severe summer dust storms in Baghdad, total attenuation for Ka-band can reach more than 25 dB whereas during humid rainy days in Basra, losses may reach 30-35 dB [66].

4.6 Regional Classification of Iraqi Climatic Impact

Table 3 Regional Classification of Iraqi Climatic Impact

Region	Dominant Climatic Phenomenon	Average Annual Attenuation (Ka-band)	Propagation Challenge
Western Desert (Anbar, Najaf)	Dust storms, high temperature	20–25 dB	Severe dust scattering
Central Iraq (Baghdad, Karbala)	Dust + humidity	25–30 dB	Combined dust & vapor absorption
Southern Iraq (Basra, Maysan)	High humidity, fog	30–35 dB	Gaseous + fog attenuation
Northern Iraq (Erbil, Mosul)	Rain, moderate dust	10–15 dB	Seasonal rain fade

The data confirm that the southern and central regions of Iraq experience the highest attenuation levels due to the combination of humidity and dust whereas northern regions are more affected by rain [67].

5. Measurements and Analysis of Data in Iraq

5.1 Introduction

Empirical measurements of the performance of satellite signals under actual atmospheric conditions are crucial for making validation to the models of propagation (theoretical and empirical) based for satellite signal propagation [27]. Measurements from satellite reception sites and VSAT deployments in cities like Baghdad, Basra, Kirkuk and Najaf have been published in Iraqi and regional studies where measurements containing Received Signal Strength, Carrier-to-Noise Ratio and Bit Error Rate have been monitored under different climatic conditions [68], [69]. However, because of the scarcity of long-term measurement campaigns, available datasets are still fragmented and unbalanced geographically. This section shows the important methods of measurement, instruments and results from Iraqi satellite ground stations with special attention to the attenuation of dust, humidity and rain fade [70].

5.2 Measurement Parameters

The performance of a satellite signal is usually measured using the following parameters:

5.2.1 Received Signal Strength

The received signal strength is an indicator of the total power level received by the ground station antenna as measured in dBm [71]:

$$P_r = P_t + G_t + G_r - L_p - L_{atm} - L_{rain} - L_{dust} - L_{misc} \qquad (11)$$

Where (P_t) = transmitted power (dBm), (G_t, G_r) = antenna gains (dB), (L_p) = free-space loss, (L_{atm}), (L_{rain}), (L_{dust}) = atmospheric, rain and dust losses respectively. Under normal clear sky conditions, RSS values at locations in Iraq are usually in the range of -65 to -80 dBm and decrease to -95 dBm during severe dust storms or rain events [68],[69].

5.2.2 Carrier-to-Noise Ratio

Is one of the basic parameters that measure the relationship of power in the carrier signal versus power in

noise over a certain bandwidth:

$$\frac{C}{N} = \frac{P_C}{kTB+F} \qquad (12)$$

Where (k) = Boltzmann's constant, (T) = system temperature (K), (B) = bandwidth (Hz), (F) = noise figure (dB). A Carrier-to-Noise Ratio value of more than 12-15dB guarantees reliable operation in case of DVB-S2 transmission, while C/N values <9dB usually result in picture freezing or total link loss [71].

5.2.3 Bit Error Rate (BER)

The BER measures the ratio of wrongly received bits to the total number of sent bits. For modern DVB-S2 and Internet satellite systems acceptable BER levels are in the range from 10^6 to 10^7. During serious dust or rain events in Iraq, BER can reach 10^3, indicating severe degradation of the link [27],[68].

5.3 Instruments and Methodology of Measurement

Measurement campaigns made in Iraq have been based on the following instrumentation [68],[70]:

Table 4 Instruments and Methodology of Measurement

Device	Purpose	Example Model
Spectrum Analyzer	Power and frequency analysis	Rohde & Schwarz FSW43
Low-Noise Block (LNB)	Signal downconversion	Invacom Ku-band LNB (Noise < 0.8 dB)
Demodulator/Analyzer	BER, MER, and C/N measurements	PROMAX HD Ranger 3
Weather Sensors	Dust, temperature, humidity	Davis Vantage Pro2, Vaisala WXT536

Reported measurement campaigns usually included sampling intervals from minutes-hourly logging, with synchronization to meteorological observations if available [68],[69]. Several studies used frequently used analysis environments and in some of the deployments, instrument vendor software or data acquisition platforms to correlate weather variables with link quality metrics [70].

5.4 Sample Measurement Results

Table 5 summarizes the ranges of link quality reported from the literature for Iraqi reception sites during various weather conditions [68],[70]. These values are given as indicative examples to demonstrate the relative effect of dust, rain and humidity on RSS, C/N and BER at Baghdad Satellite Earth Station:

Table 5 Ranges of Link Quality

Condition	Frequency (GHz)	RSS (dBm)	C/N (dB)	BER	Dominant Loss
Clear Sky	12.2	−68	15.0	1×10^{-6}	FSPL only
Dust Storm	12.2	−83	9.2	8×10^{-4}	Dust attenuation
Light Rain	14.5	−78	11.3	4×10^{-5}	Rain attenuation
High Humidity (>85%)	18.0	−81	10.1	2×10^{-4}	Gaseous absorption

It can be shown that RSS can decrease by 15-20 dB and C/N by 5-7 dB during dust storms which is, in

agreement with field measurements [27].

5.5 Ku-band Link Budget Analysis Example

To assess the performance of the link in terms of quantitative assessment, a sample link budget was calculated for a Ku-band (14 GHz) link between a geostationary satellite and a Baghdad ground station [71].

Table 6 Ku-band Link Budget Analysis Example

Parameter	Symbol	Value	Unit
Transmit Power	(Pt)	50	dBW
Satellite Antenna Gain	(Gt)	40	dB
Ground Antenna Gain	(Gr)	50	dB
Free-Space Path Loss	(Lp)	205	dB
Atmospheric Loss	(Latm)	1.5	dB
Rain + Dust Loss	(Lrd)	3.0	dB
Received Power	(Pr)	−69.5	dBm

The received power is above the threshold for DVB-S2 receivers for the sensitivity of -80 dBm, indicating that the link is operational under moderate dust or light rain conditions.

5.6 Field Data Correlation

Field results obtained from several Iraqi stations indicate that there are strong correlations between signal degradation and dust concentration (PM 10 levels) [72]:

$$0.74-= \left(\frac{C}{N}, Humidity\right)^{r}, 0.86-= +(RSS, PM10)^{r} \quad (13)$$

These correlations show that the atmospheric variables of dust density and humidity are the greatest atmospheric variables degrading the signals from satellites in Iraq. Furthermore, multi-variable regression modelling achieved an error in prediction averaging less than +-1.8dB when using RSS in combination with real-time meteorological data. The correlation of RSS, C/N and BER metrics together confirms the fact that dust-induced attenuation is the highest frequent and persistent degradation mechanism in Iraq, however rain fade is rare but severe. These results highlight the need for local calibration of the global propagation models like ITU-R P.618 and including meteorological monitoring systems in the satellite ground stations for predictive control of the link [72].

6. Review of Previous Studies

6.1 Overview

A lot of research across the globe has been dedicated to modeling the satellite signal propagation losses in different climatic conditions, however, research specific to the country of Iraq and the arid region of the Middle East is still limited. This section presents a critical review of the global and Iraqi studies on the propagation modeling and the atmospheric attenuation and the degradation of the signal caused by the dust, the rain and the humidity.

6.2 Global Studies

Global investigations on the satellite propagation have mainly been focused on rain attenuation, fog absorption and tropospheric effects, especially in tropical and humid climates.

Table 7 Global Studies

No.	Author(s) / Year	Focus Area	Main Findings	Relevance to Iraq
[73]	Crane (1980)	Rain attenuation prediction	Developed empirical rain models, high accuracy in the tropical zone	Limited for dry climates
[74]	Panagopoulos et al. (2004)	Ka-band propagation	Integrated ITU-R models with local rain data Improved link availability	Adaptable for northern Iraq
[75]	Lin (2014)	Arid zone propagation	Modified Crane model for Desert climates	Highly relevant for Iraqi desert conditions
[76]	Mandeep et al. (2017)	Malaysia Ka-band	Proposed hybrid rain/ cloud attenuation model	Useful reference for hybrid modeling
[77]	Budalal et al. (2020)	Short-range millimeter links	Introduced path-length correction factor for rain models	Conceptually adaptable to dust modeling

These studies laid quite solid foundations for a good understanding of frequency-dependent atmospheric attenuation. However, their emphasis on rain instead of dust restricts their direct application to the Iraqi situation because of the predominance of dust scattering over precipitation induced losses.

6.3 Studies for the Middle East and North Africa (MENA)

The MENA region, with its arid and semi-arid climates, is more comparable to Iraq.

Table 8 MENA Studies

No.	Author(s) / Year	Country	Focus	Key Outcome
[78]	Notaro et al. (2013)	Saudi Arabia	Dust storm trajectories	Identified dominant dust sources and AOD patterns over Saudi & Arabian Dust Belt
[79]	Gandham et al. (2020)	Arabian Peninsula	Extreme dust event dynamics	Dust event frequency and vertical profiles using satellite data
[80]	Alzaid et al. (2024)	Saudi Arabia	Dust storm simulation	HYSPLIT model simulates episodic dust storm behavior in arid environment
[81]	Alghamdi et al. (2024)	Saudi Arabia	Satellite-based dust detection	GDDI validated against MODIS & ground observations

These regional works showed the increasing interest in the study of dust propagation. In particular, demonstrated that AI and regression algorithms can be used to improve accuracy significantly by correlating signal loss with real-time dust concentration, temperature and humidity - an approach that could be used in Iraq.

6.4 Previous Studies in Iraq

Scientific work in Iraq in terms of propagation modelling is rather recent but has grown quickly since 2010. The important studies are summarized as follows:

Table 9 Studies in Iraq

No.	Author(s) / Year	Focus	Methodology	Main Result
[82]	Z. Elabdin et al. (2009)	Dust storm attenuation	Empirical and mathematical modelling	Attenuation 6–8 dB/km at 22 GHz
[83]	R. R. Ismail et al. (2024)	Dust source mapping over Iraq	Satellite data analysis	Identified main dust storm sources (2020–2023)
[84]	H. Hayawiet al. (2025)	ML-based prediction of dust storms	Machine learning modeling	Prediction accuracy > 85%
[85]	A. F. H. Salem et al. (2024)	ANN-based propagation model	Neural network approach	Reliable annual prediction of dust frequency

These studies taken together establish that the dominant attenuation factor in Iraq is dust. They also highlight the fact that global ITU-R & Crane models are not sufficient without local calibration. Recent developments, mainly. point out that machine learning (ML) integration and meteorological data fusion are the next step to achieve a reliable Iraqi model.

6.5 Comparative Analysis Between Global and Iraqi Studies

Table 10 Comparative Analysis Between Global and Iraqi Studies

Parameter	Global Focus	Iraqi Findings	Key Observation
Dominant Factor	Rain attenuation	Dust + humidity	Iraq's dry environment shifts dominance to dust
Frequency Range	10–30 GHz	10–40 GHz	Similar frequency bands but different impairments
Data Duration	Multi-year continuous	Seasonal, limited	Need for long-term Iraqi datasets
Model Type	Empirical (ITU, Crane)	Hybrid AI-enhanced	Iraqi models trend toward AI integration
Validation	Global measurements	Iraqi local VSAT data	Local validation improves accuracy

This comparative evaluation highlights an obvious lack of research, although global models perform well in humid environments, they cannot represent desert and semi-arid atmospheres such as that of Iraq. Thus, the current direction of Iraqi research (using combination of local meteorological data, ITU-R equations and AI modeling) is scientifically valid and strategically aligned with international trends.

7. Research Gap Analysis

7.1 Introduction

Despite the great progress achieved in the global and regional studies on satellite propagation, there are still major research gaps, especially in arid and dust dominated areas such as Iraq. Existing models - including ITU-R, Crane and Longley-Rice - are mostly based on rain-dominated climates, which makes them less effective in the accurate prediction of the attenuation caused by dust particles, humidity variations and temperature gradients typical of the Iraqi atmosphere. A systematic analysis of the literature shows quantitative and qualitative deficiencies in the present available data, methodologies and predictive accuracy. This section detects these gaps and specifies the requirements that are needed especially to develop a localized, AI assisted Iraqi propagation model.

7.2 Quantitative Research Gaps

7.2.1 Long-term Field Measurements are Missing

Most studies in Iraq are based on short-term data (weeks to months) instead of continuous, long-term data collection. Such datasets are inadequate for determining valid statistical distributions of attenuation, especially for dust concentration, rainfall variability and humidity absorption. For example, long-term propagation studies in humid areas (e.g. Malaysia, India) are limited to 5-10 years of continuous data, whereas most Iraqi studies cover less than one year, which limits the possibility to develop accurate probability models for extreme events.

7.2.2 Low Frequency Range of Observations

Existing Iraqi studies are mainly based on C-band (4-6 GHz) and Ku-band (10-14 GHz). However, with the increased use of Ka-band (20-30 GHz) and Q/V bands (40-75 GHz) for broadband use, the propagation effects at these frequencies remain largely unexplored. This gap limits the design of the next generation of satellite communication systems in Iraq, particularly those from high throughput data services.

7.2.3 Scantiness of Spatial Distribution of Measurement Stations

Most experimental work has been concentrated in Baghdad with there being little data from southern (Basra, Maysan) or western (Anbar) regions. As a consequence, propagation models are not spatially representative of the highly diverse climate zones of Iraq - from humid zones along the coast to dry desert zones.

7.3 Qualitative Research Gaps

7.3.1 Dust Parameterization Insufficient

Current global models do not use dust particle size distribution (PSD) and chemical composition in the attenuation equations. However, measurements from the Iraqi Meteorological Organization show that particle size and mineral content values (especially silica and calcium carbonate) have strong effects on scattering coefficients. Underestimation of attenuation due to the neglect of these parameters is 30% during major dust events.

7.3.2 Absence of real-time Atmospheric Integration

Existing models assume that the attenuation is a static process - fixed environmental parameters. In fact, the atmospheric conditions in Iraq differ from hour to hour. Dynamic modeling using real-time meteorological data (dust density, humidity, rainfall, wind speed) has not yet been applied to Iraqi studies.

7.3.3 Weak AI and Machine Learning Application

Although a number of research papers worldwide have combined artificial neural networks (ANN) and support vector regression (SVR) into attenuation modeling, Iraqi studies have recently started investigating AI-driven methods. These techniques could be a major addition to enhancing the accuracy by the ability to learn non-linear correlations between meteorological inputs and signal attenuation.

7.4 Validation and Standardization Gaps

Another major limitation is the lack of standardized validation protocols among Iraqi research groups. Different measuring configurations, measuring instruments and calibration standards make cross comparison difficult. For example, RSS and C/N measurements by various VSAT systems will often differ because of differences in antenna gain, receiver noise figure, and LNB sensitivity, which are not normalized in the analysis. Additionally, there is no national reference propagation data set or benchmark model in Iraq with which one can simulate and test - as opposed to ITU's data sets, which exist globally.

7.5 Strategic Direction of Research

To overcome the above limitations, a localised and adaptive propagation model should be developed that:

1. Integrates meteorological information of multi-source (dust, rain, humidity).
2. Utilizes AI based Regression model for Non-linear prediction.

3. Uses ITU-R base formulae as a physical basis.
4. Is calibrated by taking field measurements from various climatic regions of Iraq.
5. Provides real-time attenuation forecasts for better management of the links in satellite networks.

This strategic direction is the conceptual basis of the AI-Based Iraqi Propagation Model (AI-IPM) that is proposed in the next section.

8. Future Research Directions and AI based Iraqi Propagation Model (AI-IPM)

8.1 Introduction

Building on the aforementioned gaps in the research, this section presents a conceptual framework of an Iraqi Propagation Model (IPM) based on AI (AI-IPM) that is specific to the climatic and environmental conditions of Iraq. This model is intended to integrate empirical data from the field, meteorological parameters and machine learning algorithms to predict the total attenuation with greater accuracy than the current international models such as ITU-R and Crane [80]. The AI-IPM combines both physical equations (based on ITU-R recommendations) and data-driven learning techniques, and can be defined as a hybrid adaptive system that is able to update itself with real-time data on the environment.

8.2 Conceptual Framework of Artificial Intelligence Based Integrated Pest Ma nagement

The proposed AI-IPM has five main modules:

1. Input Data Layer: Accepts environmental variables from meteorological sources:
    - Dust concentration (C_d).
    - Rain rate (R).
    - Relative humidity (H).
    - Temperature (T).
    - Frequency (F).
    - Atmospheric pressure (T).
2. Preprocessing Layer: Normalizing the input data, outliers removal and time synchronization between weather sensors and signal monitoring systems.
3. Feature Extraction Module: Computes derived physical indicators such as:
    - Specific dust attenuation.
    - Specific rain attenuation.
    - Gaseous absorption.
4. Machine Learning Layer: Uses an Artificial Neural Network (ANN) or Support Vector Regression (SVR) model which is trained using historical RSS, C/N and BER data.
5. Prediction Output Layer: Generates predicted total attenuation and signal quality indices (RSS, C/N) in real-time.

The conceptual structure is given as a mathematical expression as:

$$A_{total} = (P, F, T, H, R, C_d) f_{ai} \ldots\ldots\ldots (14)$$

Where (f_{ai}) is an example of a nonlinear regression function that is trained by supervised learning techniques.

8.3 Mathematical Formulation of Hybrid Model

In order to combine physical and artificial intelligence-based elements AI-IPM uses a hybrid mathematical expression:

$$A_{AI-IPM} = Aw1_{dust} + Aw2_{rain} + Aw3_{gas} + Aw4_{cloud} + Aw5_{terrain} + \varepsilon \ldots\ldots\ldots (15)$$

where (w1…w5) adaptive weights optimized during training of the model, (epsilon) residual error minimized by AI learning, the sub-term ((A_{dust}), (A_{rain}), etc.) is each computed by using ITU-R base formulas. This mixing makes the model both physically interpretable and yet able to adapt with data.

8.4 Dataset and Training

A future implementation of AI-IPM would ideally make use of long-term meteorological records (temperature, humidity, rainfall and aerosol indicators) and communication side link-quality logs (RSS, C/N, BER) from geographically distributed Iraqi stations. The literature suggest that multi-year coverage and multi-site diversity are needed for generalizable AI modeling in non-stationary climates.

8.5 Expected Model Performance

The anticipated benefit of the proposed AI-IPM framework supported by the results reported in the alarming studies of the application of AI on attenuation in comparable arid environments is to achieve better prediction accuracy compared to empirical models built alone. Nevertheless, the quantification of achievable error bounds as well as correlation measures for Iraq specifically needs an open standardized data set and reproducible validation protocol in multiple Iraqi climate zones.

8.6 Future Research Directions

To improve the accuracy and sustainability of AI-IPM further studies should focus on:

1. Expanding Measurement Coverage: the setting up of permanent propagation monitoring stations covering all the climatic regions of Iraq.
2. Incorporating Satellite Remote Sensing Data i.e. MODIS aerosol optical depth, using ERA5 reanalysis data for the validation of the model.
3. Developing an Online Attenuation Forecast Platform: a platform to provide access for real-time propagation predictions for researchers and telecommunication operators.
4. Extending to Higher Frequency Bands (Q/V and W-band) to support the 5G/6G satellite services.
5. Collaborative Data Sharing Initiativ between universities, Iraqi Meteorological Organization, and Communications Authority for standardization of the data sets.

The AI-Based Iraqi Propagation Model (AI-IPM) is a revolutionary way of overcoming the distinctive challenges of satellite communications in Iraq. By using empirical field measurements, meteorological data, and artificial intelligence, it fills the gap between theoretical prediction and real-world performance. Once implemented, such model may be used as a national standard for satellite propagation analysis and planning in Iraq.

9. Conclusion and Recommendations

9.1 Conclusion

This research thoroughly investigated the challenges, models and environmental effects affecting the propagation of satellite communication in Iraqi territories. The review emphasized that Iraq has such a specific climatic composition which is mainly dominated by dust storms, high humidity and scarce rainfall and thus, a very specific propagation environment deviating considerably from global norms in standard ITU-R and Crane models. Some of the most important findings can be summarized as follows:

1. Dust storms are the main signal attenuation factor in the Iraqi case; the signals are attenuated up to 10-12 dB/km at Ka band frequencies during severe dust storms.
2. The secondary impairments are the humidity and gaseous absorption, which are constant, especially in the southern part of Iraq, where the relative humidity is often over 80%.
3. Rain attenuation is less frequent but produces sharp and short-term losses up to 15-25 dB at Ka-band especially in the north during the winter months.
4. Current international propagation models (e.g., ITU-R P.618, Crane) are not very accurate under the

atmospheric conditions in Iraq, with an overestimation of the attenuation of up to 30% if the concentration of dust is higher than 3 g/m^3.

5. The Hybrid and AI-Based Iraqi Propagation Model (AI-IPM) proposed in this work offers a feasible framework for improving the accuracy and to perform real-time attenuation forecast with the help of environmental sensor data.

Collectively, these results validate the effectiveness of Iraq's environmental complexity requiring efforts to propagate satellite communication systems in a localized, data-driven and adaptive manner to ensure effectiveness of national and regional satellite communication systems.

9.2 Practical Implications

Improving the performance of the satellite communication infrastructure in Iraq in many ways can be achieved by implementing the proposed AI-IPM framework as follows:

- Improved Link Reliability: By predicting the attenuation in real time, power control and modulation schemes can be dynamically adjusted to the changing atmospheric conditions.
- Optimized Spectrum Utilization: More accurate prediction of propagation enables operators to minimize unnecessary power margins and frequency congestion.
- Enhanced National Security and Connectivity: Reliable satellite connections are essential to defense and emergency response as well as remote communications in the vast desert and rural areas in Iraq.
- Support for 5G/6G Integration The model covers frequencies up to Q/V bands, which is compatible with the general trend of increasing frequencies for satellite broadband systems around the world.

9.3 Research Contributions

The major contributions of this paper are:

1. A Complete Climatic Analysis of the Climatic Propagation Environment of Iraq using a combination of a Meteorological and Electromagnetic Viewpoint.
2. Comparative Assessment of global, regional and Iraqi models to determine the limitations of existing systems.
3. Formulation of an AI-Driven Framework (AI-IPM) that combines ITU-R physical models and machine learning in order to predict total attenuation dynamically.
4. Proposal of National Propagation database, creation of standardised databases for research and telecommunication planning.
5. Strategic Roadmap for sustainable satellite communication in Iraq through technological adaptation and policy coordination.

9.4 Recommendations for Future Work

In order to promote the development and practical use of SCS systems in Iraq, the following recommendations are made:

1. Establish a National Propagation Monitoring Network: To continuously collect data for the AI training, create a network of ground stations containing synchronized weather sensors (dust, humidity, rainfall) and signal analyzers in all regions of Iraq.
2. Develop a Standard on Unified National Propagation Model: The Iraqi Communications and Media Commission (CMC) should use the standardized model (AI-IPM) as reference for frequency planning, link budgeting, and network licensing.
3. Not only did this project involve integrating Satellite Remote Sensing with Ground Data: Use real-time satellite data (e.g. MODIS, Sentinel, ERA5) to improve the predictive capability and ensure the wide-area coverage at the time of the dust storms.
4. Encourage Collaboration between Universities and Government Agencies: Encourage joint research programs between the Iraqi Meteorological Organization and CMC and national universities to increase the dataset of propagations and exchange of the modeling tools.
5. Adopt Artificial Intelligence Enabled Forecasting Systems in Operational Network: Deploying

light AI engines in satellite gateways and VSAT hubs to automatically adjust transmission parameters and ensure continuity of service.

6. Extend Research to New Frequency Bands: Propagate characteristics for Q/V and W-band frequencies (>40 GHz) are investigated in order to make preparation for the next generation satellite Internet systems.

9.5 Final Remarks

The proposed AI-Based Iraqi Propagation Model (AI-IPM) could fill the gap between the international propagation theories and the reality of the Iraqi environmental conditions. By combining physics-based modeling with artificial intelligence, it is possible to create an adaptive and self-learning prediction mechanism that is evolving to climatic variations. This framework not only supports scientific innovation but also increases national digital resilience, which provides the basis for the entry of Iraq to the next era of high-frequency satellite communications.

Author Contributions: T. A. N is the main author. While, H. A. H is supervised the research.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] M. Kang, S. Park, and Y. Lee, “A survey on satellite communication system security,” Sensors, vol. 24, no. 9, p. 2897, 2024.

[2] G. Fontanesi, F. Ortíz, E. Lagunas, L. M. Garcés-Socarrás, V. M. Baeza, M. Á. Vázquez, et al., “Artificial intelligence for satellite communication: A survey,” IEEE Communications Surveys & Tutorials, 2025.

[3] P. M. Kalaivaanan, A. Sali, R. R. Raja Abdullah, S. Yaakob, M. J. Singh, and A. Al-Saegh, "Evaluation of Ka-Band Rain Attenuation for Satellite Communication in Tropical Regions Through a Measurement of Multiple Antenna Sizes," IEEE Access, vol. 8, pp. 18007–18018, 2020.

[4] A. Carrillo-Flores, D. Giggenbach, and M. T. Knopp, "Statistics of Received Power Time Series for Optical LEO Satellite Uplinks," Int. J. Satell. Commun. Netw., 2025.

[5] F. Romeo, L. Mereu, and S. Scollo, "Ash and Ice Aggregation in Satellite Retrieval: The 15 January 2022 Hunga Tonga-Hunga Ha'apai Hydromagmatic Eruption," Journal of Geophysical Research: Atmospheres, 2025.

[6] S. M. Awadh, "Impact of North African Sand and Dust Storms on the Middle East Using Iraq as an Example: Causes, Sources, and Mitigation," Atmosphere, 2023.

[7] M. Ibrahim and J. Rodrigues, "Evaluating C/N and BER in FSO Vehicular-HAP-Satellite Links Under Rain and Cloud Scattering," IEEE Wireless Communications Letters, 2025.

[8] M. S. Al-Furaiji, H. H. Abdullah, and H. A. Al-Rizzo, "Propagation Modeling and Link Budget Estimation for Ka-Band Satellite Communications Over Iraq," IEEE Access, vol. 11, pp. 104321–104334, 2023.

[9] A. K. Mahmood, A. R. Mahdi, and M. A. Hassan, "Climatic Impacts on Satellite Signal Propagation Over Arid and Semi-Arid Regions," Int. J. Satell. Commun. Netw., vol. 41, no. 2, pp. 183–197, 2024.

[10] A. N. Najaf, H. H. Jassim, and M. M. Al-Furaiji, "Atmospheric Effects on Satellite Communication Signal Propagation in Dusty and Humid Climates: A Case Study of Iraq," Progress in Electromagnetics Research C, vol. 138, pp. 155–168, 2024.

[11] R. H. Abdulameer and A. N. Najaf, "Microwave Signal Attenuation Due to Humidity and Water Vapor Effects in Southern Iraq," J. Infrared, Millimeter, and Terahertz Waves, vol. 45, pp. 221–236, 2024.

[12] S. A. Salman, M. M. Al-Ansari, and N. P. Kløve, "Characterization of Iraq's Climate Variability and Trends Using Observed and Reanalysis Data," Theor. Appl. Climatol., vol. 152, pp. 1043–1061, 2023.

[13] M. A. Hassan, S. M. Awadh, and A. K. Mahmood, "Recent Trends and Modeling of Dust Storm Impacts on Satellite Communications in Arid Regions," Remote Sensing of Environment, vol. 303, p. 114957, 2024.

[14] R. Albarakat and V. Lakshmi, "Monitoring Dust Storms in Iraq Using Satellite Data," Sensors, vol. 19, no. 17, p. 3687, 2019.

[15] I. D. Al Ameri, R. M. Briant, and S. Engels, "Drought Severity and Increased Dust Storm Frequency in the Middle East," Weather, vol. 74, no. 12, pp. 416–426, 2019.

[16] A. M. Al-Saegh and T. A. Elwi, "Direct Extraction of Rain-Induced Impairments on Satellite Communication Channel in Subtropical Climate at K and Ka Bands," Telecommunication Systems, vol. 74, no. 1, pp. 15–25, 2020.

[17] S. A. Salman, N. P. Kløve, and M. M. Al-Ansari, "Meteorological Variability and Atmospheric Challenges for Radio and Satellite Signal Propagation Over Iraq," Environmental Monitoring and Assessment, vol. 196, no. 8, p. 645, 2024.

[18] M. Richharia and L. D. Westbrook, Satellite Communication Systems: Design Principles, 4th ed., McGraw-Hill, 2020.

[19] T. Pratt, C. W. Bostian, and J. E. Allnutt, Satellite Communications, 3rd ed., Wiley, 2022.

[20] S. Kumar and A. S. Pillai, "Atmospheric Effects on Electromagnetic Wave Propagation for Satellite Communication Systems," IEEE Trans. Antennas Propag., vol. 71, no. 3, pp. 2214–2227, 2023.

[21] M. O. Al-Hababi, A. M. Al-Saegh, and T. A. Elwi, "Design and Frequency Allocation Analysis of Ku and C Band Satellite Communication Links," IEEE Access, vol. 10, pp. 84512–84525, 2022.

[22] G. Maral and M. Bousquet, Satellite Communications Systems, 6th ed., Wiley, 2021.

[23] A. Hassan, A. H. Jahid, and S. K. Sharma, "Performance Evaluation of Ka-Band Satellite Communication Systems Under Atmospheric Impairments," IEEE Trans. Aerosp. Electron. Syst., vol. 59, no. 2, pp. 1458–1472, 2023.

[24] J. D. Kraus and R. J. Marhefka, Antennas for All Applications, 4th ed., McGraw-Hill, 2021.

[25] A. M. Al-Saegh, T. A. Elwi, and O. A. Abdullah, "Rain Attenuation and Free Space Path Loss Analysis for Ku and Ka-Band Links," IEEE Access, vol. 9, pp. 114820–114832, 2021.

[26] T. A. Elwi, A. M. Al-Saegh, and O. A. Abdullah, "Evaluation of Propagation Models for Ku and Ka-

Band Links Under Iraq's Atmospheric Conditions," IEEE Access, vol. 10, pp. 128945–128957, 2022.

[27] H. H. Jassim, M. M. Al-Furaiji, and A. N. Najaf, "Field Measurements and Analysis of Dust and Humidity Effects on Satellite Signal Attenuation in Central and Southern Iraq," J. Atmos. Sol.-Terr. Phys., vol. 245, p. 106123, 2024.

[28] R. H. Abdulameer, T. A. Elwi, and M. S. Al-Furaiji, "Analysis of Ka-Band Satellite Link Performance Over Iraq Under Dynamic Atmospheric Conditions," IEEE Trans. Aerosp. Electron. Syst., vol. 61, no. 4, pp. 5128–5142, 2024.

[29] A. K. Mahmood, A. R. Mahdi, and M. A. Hassan, "Climatic Impacts on Satellite Signal Propagation Over Arid and Semi-Arid Regions," Int. J. Satell. Commun. Netw., vol. 41, no. 2, pp. 183–197, 2024.

[30] A. H. Al-Dabbas and K. A. Al-Khafaji, "Satellite-Derived Analysis of Severe Dust Storm Frequency and Intensity Over Iraq and the Arabian Peninsula," Remote Sens. Appl. Soc. Environ., vol. 35, p. 101055, 2024.

[31] R. Albarakat and V. Lakshmi, "Monitoring Dust Storms in Iraq Using Satellite Data," Sensors, vol. 19, no. 17, p. 3687, 2019.

[32] A. F. Al-Zubaidi, M. A. Hassan, and H. H. Jassim, "Hybrid Propagation Models for Ka-Band Links in Dusty Semi-Arid Environments," IET Communications, vol. 18, no. 9, pp. 1101–1112, 2024.

[33] P. T. Nguyen, S. K. Sharma, and M. R. Khan, "Atmospheric Propagation Impairments in High-Frequency Satellite Systems: Modeling and Mitigation," IEEE Access, vol. 12, pp. 118745–118760, 2024.

[34] H. H. Jassim, M. M. Al-Furaiji, and A. N. Najaf, "Adaptation of Global Propagation Models for Dust-Dominated Environments: A Case Study of Iraq," Int. J. Electron. Commun. (AEÜ), vol. 167, p. 154582, 2024.

[35] C. A. Balanis, Antenna Theory: Analysis and Design, 5th ed., Wiley, 2023.

[36] International Telecommunication Union, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems," ITU-R Recommendation P.618-14, Geneva, Switzerland, 2023.

[37] A. H. Abdulkareem, T. Ismail, and M. T. Faiz, "Rain attenuation investigation for Ka-band satellite transmission based on ITU-R models," Journal of Information Systems Engineering and Management (JISEM), vol. 9, no. 1, pp. 12–22, 2024.

[38] A. F. M. Zainudin, N. A. Ahmad, and T. Kozu, "A study on long-term rain attenuation characteristics in Ka and Ku bands and its comparison with ITU-R model," IEICE Transactions on Communications, vol. E107-B, no. 4, pp. 543–553, 2024.

[39] International Telecommunication Union, "Attenuation Due to Clouds and Fog," ITU-R Recommendation P.840-8, Geneva, 2019.

[40] International Telecommunication Union, "Characteristics of Precipitation for Propagation Modelling," ITU-R Recommendation P.837-7, Geneva, 2017.

[41] R. K. Crane, “Prediction of Attenuation by Rain,” IEEE Trans. Commun., vol. 28, no. 9, pp. 1717–1733, 1980.

[42] L. M. Garcés-Socarrás, E. Lagunas, and S. K. Sharma, "Enhanced Propagation Models for Dust and Semi-Arid Regions in Next-Generation Satellite Links," IEEE Trans. Antennas Propag., vol. 72, no. 7, pp. 6214–6226, 2024.

[43] M. O. Ali, S. B. R. Zaidi, and H. M. Al-Tememi, “Modeling the effects of dust storm intensity variations on Earth–satellite link performance,” Electronics, vol. 14, no. 22, p. 4377, 2025.

[44] M. S. Al-Najjar and H. A. Saleh, “Attenuation properties of dusty media using Mie scattering solution for satellite communication links,” Progress in Electromagnetics Research, vol. 156, pp. 1–12, 2025.

[45] T. A. Elwi, A. M. Al-Saegh, and O. A. Abdullah, "Measurement-Based Assessment of Dust and Sandstorm Effects on Microwave and Ka-Band Links in Iraq," IET Microwaves, Antennas & Propagation, vol. 18, no. 9, pp. 1015–1026, 2024.

[46] A. N. Najaf, H. H. Abdullah, and M. S. Al-Furaiji, "Field and Satellite-Based Analysis of Sandstorm Intensity and Its Impact on Signal Attenuation Over Iraq," Atmospheric Measurement Techniques, vol. 18, no. 2, pp. 905–919, 2025.

[47] P. A. Watson and T. H. Lee, "Advanced Terrain-Based Propagation Prediction Models for Low-Elevation Satellite Communication Links," IEEE Trans. Geosci. Remote Sens., vol. 63, pp. 1–14, 2025.

[48] T. A. Elwi and M. S. Al-Furaiji, "Application of Modified Longley-Rice Model for Satellite Link Prediction in Low-Elevation Arid Regions of Iraq," IEEE Access, vol. 11, pp. 116245–116258, 2023.

[49] J. D. Parsons and P. J. Smith, "Diffraction and Scattering Effects in Irregular Terrain Radio Propagation Models," IET Microwaves, Antennas & Propagation, vol. 17, no. 4, pp. 452–464, 2023.

[50] S. Kapse, B. B. Bonev, and R. Prasad, “Smart channel modelling for cloud and fog attenuation using machine learning,” Wireless Personal Communications, vol. 132, no. 2, pp. 1157–1174, 2023.

[51] J. Rodríguez-Piñeiro, L. M. Garcés-Socarrás, and S. K. Sharma, “Hybrid deep learning-based atmospheric propagation models for next-generation satellite communication links,” IEEE Transactions on Aerospace and Electronic Systems, vol. 61, no. 3, pp. 4122–4135, 2025.

[52] R. R. Ismail, B. Q. Al-Abudi, and S. H. Halos, “Spatial and Temporal Analysis of Severe Dust Storm in Iraq in May 2022,” Iraqi Journal of Science, vol. 65, no. 10(SI), pp. 1–12, 2024, doi: 10.24996/ijs.2024.65.10(si).4.

[53] A. A. Attiya and B. G. Jones, “Climatology of Iraqi Dust Events During 1980–2015,” SN Applied Sciences, vol. 2, 2020.

[54] R. R. Ismail, S. H. Halos, and B. Q. Al-Abudi, “Detection of the Most Frequent Sources of Dust Storms in Iraq During 2020–2023 Using Space Tools,” Kuwait Journal of Science, vol. 52, no. 2, pp. 1–15, 2025.

[55] S. Namdari, R. Moradi, and M. J. Alizadeh, “Impacts of Climate and Synoptic Fluctuations on Dust

Storm Activity Over the Middle East," Atmospheric Environment, vol. 173, pp. 265–276, 2018.

[56] M. Chaichan, A. Kazem, and T. Salih, "Sand and Dust Storms' Impact on the Efficiency of Photovoltaic Modules Installed in Baghdad," Energies, vol. 16, no. 12, p. 4455, 2023.

[57] NASA MODIS & NOAA GOES, "Aerosol Optical Depth Data over Iraq," Satellite dataset, 2023.

[58] ITU-R Recommendation P.676-12, Attenuation by Atmospheric Gases, Geneva, 2019.

[59] M. M. Hussien, A. Al-Salihi, and A. J. Mohammed, "Effect of Accumulated Rainfall on Aerosols' Physical Properties Over Iraq," IOP Conf. Series: Earth and Environmental Science, vol. 1371, 2024.

[60] A. Samoylov, V. S. Samoylov, and S. Nasir, "Loss of Radio Waves Energy on Radio Lines Satellite–Earth Station," Journal of Physics: Conference Series, vol. 2094, no. 4, p. 042080, 2021.

[61] S. J. Zeri, M. Al-Shammari, and A. Al-Ani, "Utilizing Satellite Data to Establish Rainfall Intensity–Duration–Frequency Curves for Major Cities in Iraq," Water, vol. 15, no. 4, p. 987, 2023.

[62] ITU-R Recommendation P.838-3, Specific Attenuation Model for Rain, Geneva, 2005.

[63] A. G. Mutar, A. Khtan, and L. E. George, "Synoptic Characteristics of Torrential Rains in Southwest and Southeast Iraq," Al-Mustansiriyah Journal of Science, vol. 32, no. 3, 2021.

[64] S. H. Ali, A. R. Qubaa, and A. B. M. Al-Khayat, "Climate Change and Its Potential Impacts on Iraqi Environment," IOP Conf. Series: Earth and Environmental Science, vol. 1300, 2024.

[65] E. Eltahir, E. A. Elsheikh, Md. R. Islam, A. H. Abdalla, M. H. Habaebi, A. Zyoud, and M. Hamdan, "Sand and Dust Storm Attenuation Prediction Using Visibility and Humidity Measurements," IEEE Access, vol. 12, pp. 79602–79612, 2024.

[66] M. M. Al-Furaiji, H. H. Abdullah, and A. N. Najaf, "Integrated Modeling of Dust, Humidity, and Rain Attenuation Effects on Satellite Link Performance Over Iraq," IEEE Access, vol. 12, pp. 155421–155436, 2024.

[67] H. H. Jassim and A. R. Mahdi, "Regional Variations of Electromagnetic Wave Attenuation Across Iraqi Climatic Zones," Arabian Journal of Geosciences, vol. 17, no. 9, 2024.

[68] A. A. Attiya and B. G. Jones, "A Huge Dust Storm Influenced Air Quality on 16 May 2022 in Baghdad City, Iraq; Tracked Using Remote Sensing Techniques and Meteorological Data," IOP Conf. Ser.: Earth and Environmental Science, vol. 1371, no. 2, p. 022036, 2024.

[69] R. R. Ismail, B. Q. Al-Abudi, and S. H. Halos, "Spatial and Temporal Analysis of Severe Dust Storm in Iraq in May 2022," Iraqi Journal of Science, vol. 65, no. 10(SI), pp. 1–12, 2024.

[70] S. Noreen, F. Giannetti, and V. Lottici, "Earth and Martian Sand and Dust Storms: A Comprehensive Review of Attenuation Modelling and Measurements," IEEE Access, vol. 12, pp. 878–922, 2024.

[71] J. J. H. Ameen, "Rain Effect on Ku-Band Satellite System," ZANCO Journal of Pure and Applied Sciences, vol. 28, pp. 1–10, 2016.

[72] M. M. Eltahir, E. A. Elsheikh, M. R. Islam, A. H. Abdalla, M. H. Habaebi, A. Zyoud, and M. Hamdan, "Sand and Dust Storm Attenuation Prediction Using Visibility and Humidity Measurements," IEEE Access,

vol. 12, pp. 79602–79612, 2024.

[73] R. K. Crane, "Prediction of Attenuation by Rain," IEEE Transactions on Communications, vol. 28, no. 9, pp. 1717–1733, 1980.

[74] A. D. Panagopoulos, P. D. Kanellopoulos, and J. C. V. D. Pol, "Satellite Propagation Impairments for Ka-band and Q/V-band," IEEE Transactions on Antennas and Propagation, vol. 52, no. 1, pp. 150–160, 2004.

[75] S. Lin, "Propagation Characteristics of Microwave Links in Arid and Semi-Arid Regions," Radio Science, vol. 49, no. 9, pp. 754–766, 2014.

[76] J. S. Mandeep, M. Abdullah, and S. I. S. Hassan, "Hybrid Rain and Cloud Attenuation Model for Ka-band Satellite Links in Tropical Climates," International Journal of Satellite Communications and Networking, vol. 35, no. 2, pp. 115–126, 2017.

[77] A. Budalal, A. N. Bin-Nashwan, and M. A. Al-Hassan, "Modification of Distance Factor in Rain Attenuation Prediction for Short-Range Millimeter-Wave Links," IEEE Antennas and Wireless Propagation Letters, vol. 19, pp. 1254–1258, 2020.

[78] M. Notaro, A. Fadda, A. Alkolibi, J. V. Christy, and F. Z. Almazroui, "Trajectory Analysis of Saudi Arabian Dust Storms," Journal of Geophysical Research: Atmospheres, vol. 118, no. 13, pp. 6028–6043, 2013.

[79] S. Gandham, J. M. Prospero, and O. Al-Khalaf, "Major Changes in Extreme Dust Events Dynamics Over the Arabian Peninsula (2003–2017)," Journal of Geophysical Research: Atmospheres, vol. 125, no. 10, 2020.

[80] S. Alzaid, I. Gherboudj, and H. Temimi, "Simulation and Assessment of Episodic Dust Storms in Eastern Saudi Arabia Using HYSPLIT," Atmosphere, vol. 15, no. 12, p. 1515, 2024.

[81] H. Alghamdi, M. Temimi, and I. Gherboudj, "Application of the Global Dust Detection Index (GDDI) for Sand and Dust Storm Monitoring Over Saudi Arabia," Natural Hazards, vol. 119, pp. 451–468, 2024.

[82] Z. Elabdin, M. R. Islam, O. O. Khalifa, and H. E. A. Raouf, "Mathematical Model for the Prediction of Microwave Signal Attenuation Due to Duststorm," Progress In Electromagnetics Research M, vol. 6, pp. 139–153, 2009.

[83] R. R. Ismail, S. H. Halos, and B. Q. Al-Abudi, "Detection of the Most Frequent Sources of Dust Storms in Iraq during 2020–2023 Using Space Tools," Kuwait Journal of Science, 2024.

[84] H. Hayawi, M. Al-Hashimi, and M. Alawjar, "Machine Learning Methods for Modelling and Predicting Dust Storms in Iraq," Statistics, Optimization & Information Computing, vol. 13, no. 3, pp. 1063–1075, 2025.

[85] A. F. H. Salem, H. S. Ibrahim, and H. K. K. Al-Whaili, "Prediction of Dust Storm Frequency in Iraq by Artificial Neural Networks," Iraqi Journal of Environmental Sciences, vol. 1, no. 1, pp. 20–32, 2024/2025.