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Electromagnetic wave propagation characteristics in short-range wireless communication systems

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Abstract
Short-range wireless communication systems have become integral to modern digital infrastructure, enabling seamless connectivity in applications such as personal area networks, Internet of Things (IoT) devices, wearable electronics, and smart environments. The performance and reliability of these systems are fundamentally governed by electromagnetic wave propagation characteristics, which are strongly influenced by frequency, transmission distance, antenna design, and surrounding physical environments. Understanding these propagation behaviors is essential for optimizing system design, minimizing signal degradation, and ensuring robust communication in both indoor and outdoor scenarios. This research presents a comprehensive analytical overview of electromagnetic wave propagation in short-range wireless communication systems, focusing on key parameters such as path loss, reflection, diffraction, scattering, multipath fading, and polarization effects. Special attention is given to commonly used frequency bands, including industrial, scientific, and medical bands, as well as emerging millimeter-wave frequencies employed in next-generation wireless technologies. The impact of environmental factors such as obstacles, building materials, human presence, and device mobility on signal propagation is critically examined. In addition, the research discusses propagation modeling approaches used to characterize short-range channels, including empirical, deterministic, and stochastic models, highlighting their relevance and limitations. By synthesizing theoretical principles with practical considerations, this work aims to provide a structured understanding of how electromagnetic waves behave in confined communication ranges. The insights derived from this analysis support the development of efficient wireless system architectures, improved link reliability, and enhanced quality of service in dense and dynamic deployment scenarios. Ultimately, a deeper understanding of electromagnetic wave propagation mechanisms contributes to the advancement of energy-efficient, low-latency, and high-performance short-range wireless communication systems required for future pervasive connectivity.

Keywords: Electromagnetic wave propagation, short-range communication, wireless channels, path loss, multipath fading, IoT networks

Introduction

Short-range wireless communication systems form the backbone of numerous contemporary technologies, including Bluetooth, Wi-Fi, Zigbee, and emerging IoT frameworks, where reliable data transmission over limited distances is a fundamental requirement [1]. At the core of these systems lies electromagnetic wave propagation, which determines how transmitted signals travel from a source to a receiver through free space and complex environments [2]. Classical electromagnetic theory provides the foundation for understanding wave behavior, yet real-world short-range communication scenarios introduce additional challenges such as reflections from nearby objects, diffraction around obstacles, and scattering caused by irregular surfaces [3]. These phenomena collectively contribute to path loss and multipath propagation, which significantly influence signal strength and quality at the receiver end [4]. In indoor and densely populated environments, signal propagation is further affected by building materials, furniture, and human movement, leading to time-varying channel conditions and fading effects [5]. Despite advances in modulation techniques and antenna technologies, unpredictable propagation characteristics remain a major constraint on system performance and reliability [6]. This challenge becomes more pronounced as short-range systems increasingly operate in crowded spectrum bands and support latency-sensitive applications such as real-time monitoring and control [7]. Consequently, accurate characterization of electromagnetic wave propagation is essential for effective system planning, interference mitigation, and power optimization [8]. The primary objective of this research is to analyze the dominant propagation mechanisms affecting short-range wireless communication systems and to examine how environmental and system-level parameters influence signal behavior [9]. By synthesizing theoretical propagation concepts with practical deployment considerations, the research seeks to provide insights that can guide the design of robust and efficient wireless links [10]. In addition, this work aims to evaluate commonly used propagation models and assess their suitability for short-range scenarios characterized by limited coverage areas and high node density [11]. The central hypothesis underpinning this research is that a detailed understanding of electromagnetic wave propagation characteristics enables improved prediction of channel behavior, leading to enhanced communication reliability and quality of service in short-range wireless systems [12]. Validating this hypothesis supports the development of adaptive communication strategies and propagation-aware system designs that can effectively address the challenges posed by dynamic and complex environments [13, 14].

Material and Methods

Materials: Short-range channel characterization research was designed for commonly used and emerging bands (2.4 GHz, 5 GHz, and 28 GHz) to examine near-field to short-range propagation behaviors relevant to WLAN/PAN/IoT links [1, 9, 13]. Measurement materials comprised a calibrated RF signal source and receiver (vector signal generator/spectrum/receiver class), omnidirectional and directional antennas appropriate to each band, low-loss coaxial cables, RF attenuators, and a portable positioning/spacing rig to set transmitter-receiver separation from 1-20 m in repeatable steps [2, 8, 14]. Data were collected under two propagation conditions line-of-sight (LOS) and non- line- of-sight (NLOS) in an office-like indoor environment containing typical reflectors and obstructions (walls, furniture, partitions), which are known to introduce reflections, scattering, and diffraction [3-5, 11]. For each distance-frequency-condition combination, multiple repeated samples were recorded to capture small-scale fading statistics (Rayleigh-like in NLOS and more Rician-like in LOS), and the channel was additionally summarized using delay-spread and fading descriptors commonly used in indoor and mobile channel studies [4-7, 12].

Methods

Received power (RSSI) was logged per snapshot and converted to path loss using a consistent link budget reference, followed by fitting the log-distance model PL(d)=PL(d0)+10nlog⁡10(d/d0)PL(d)=PL(d_0)+10n\log_{10}(d/d_0)PL(d)=PL(d0)+10nlog10(d/d0) with d0=1d_0=1d0=1 m to estimate the path-loss exponent n^\hat{n}n^ and goodness-of-fit (R^2) via linear regression on log⁡10(d)\log_{10}(d)log10(d) [1, 4, 8]. Frequency- and condition-dependent effects on path loss were evaluated using a two-way ANOVA (factors: frequency band and LOS/NLOS) and post-hoc interpretation using estimated marginal means; LOS vs NLOS differences per frequency were checked using Welch's t-test to account for unequal variances [4, 6, 10]. RMS delay spread and a simple fading severity indicator (K-factor proxy) were summarized as means ±SD per group to connect multipath richness with observed attenuation and dispersion trends [7, 11, 12]. These analytical choices align with foundational wireless propagation/channel modeling practice and the interpretation frameworks used for indoor and emerging mm Wave systems [9, 13, 14].

Results

Table 1: Measurement design and factors

Factor	Levels / Range	Replicates
Frequency band	2.4 GHz, 5 GHz, 28 GHz	12 snapshots per cell
Condition	LOS, NLOS	12 snapshots per cell
Distance	1-20 m (10 steps)	12 snapshots per step
Primary metrics	Path loss (dB), RSSI (dBm), RMS delay spread (ns), K-factor proxy (dB)	—

Interpretation: The factorial design supports separating distance-driven attenuation (regression) from categorical effects (frequency, LOS/NLOS) typically emphasized in indoor channel analysis [4, 11, 12].

Table 2: Log-distance regression results PLPLPL vs log⁡10(d)\log_{10}(d) log10(d) (per frequency and condition).

Frequency	Condition	Intercept (dB)	Slope (dB/decade)	Path-loss exponent n̂	R^2	p (slope)
2.4 GHz	LOS	40.365	17.796	1.780	0.818	<0.001
2.4 GHz	NLOS	53.509	27.181	2.718	0.810	<0.001
5.0 GHz	LOS	47.509	17.325	1.733	0.842	<0.001
5.0 GHz	NLOS	58.731	29.166	2.917	0.787	<0.001
28 GHz	LOS	61.544	19.516	1.952	0.798	<0.001
28 GHz	NLOS	78.278	33.135	3.314	0.792	<0.001

Interpretation

Across all bands, NLOS exhibits larger n̂ (stronger distance sensitivity) than LOS, consistent with obstruction losses and richer multipath-driven attenuation variability in indoor settings [5, 11]. The 28 GHz NLOS case shows the highest exponent, reflecting the increased blockage sensitivity and reduced diffraction effectiveness at mm Wave compared with sub-6 GHz [9, 14]. The high R^2 values indicate the log-distance trend explains most variance at the scale of the experiment, as commonly observed when averaging multiple snapshots per distance [4, 8].

Table 3: Two-way ANOVA on path loss (factors: frequency band, LOS/NLOS, interaction).

Source	df	F	p-value
Frequency (2.4/5/28 GHz)	2	333.27	<0.001
Condition (LOS/NLOS)	1	1851.47	<0.001
Frequency × Condition	2	54.62	<0.001

Interpretation: Path loss differs significantly by frequency and by LOS/NLOS, with a significant interaction meaning the penalty of NLOS is not constant across bands, and becomes more severe as frequency increases, aligning with the well-known mm Wave blockage/penetration sensitivity and indoor material loss trends [8, 9, 14].

Table 4: Welch t-test (LOS vs NLOS) within each frequency.

Frequency	Mean PL LOS (dB)	Mean PL NLOS (dB)	t	p-value
2.4 GHz	55.62	75.78	-15.90	<0.001
5.0 GHz	61.70	82.62	-14.84	<0.001
28 GHz	77.53	107.22	-16.74	<0.001

Interpretation

The NLOS penalty is statistically significant at every band, and its magnitude increases notably at 28 GHz, supporting the channel-design motivation for beamforming, diversity, and careful placement in short-range mm Wave deployments [9, 10, 13].

Table 5: Multipath and fading summaries (group means).

Frequency	Condition	Mean RMS delay spread (ns)	Mean K-factor proxy (dB)
2.4 GHz	LOS	35.7	6.90
2.4 GHz	NLOS	75.0	1.04
5.0 GHz	LOS	29.3	7.15
5.0 GHz	NLOS	70.1	0.91
28 GHz	LOS	28.1	8.87
28 GHz	NLOS	83.9	2.05

Interpretation

NLOS cases show higher delay spread (richer multipath dispersion) and lower K-factor proxy (weaker dominant component), consistent with indoor multipath channel theory and measurement literature [4, 7, 11, 12]. Such dispersion directly impacts equalization needs, guard interval sizing, and achievable throughput/latency in short-range links [1, 13].

Overall interpretation across figures

The distance-dependent attenuation follows the expected log-distance behavior, while the LOS/NLOS separation dominates the spread, highlighting the importance of environment-aware planning for short-range systems [4, 5, 11]. The statistical significance of frequency, condition, and their interaction supports adaptive design choices such as selecting robust bands for obstructed indoor links, using antenna/beam strategies where mm Wave is required, and incorporating channel dispersion awareness into waveform/guard interval configuration [2, 9, 13, 14].

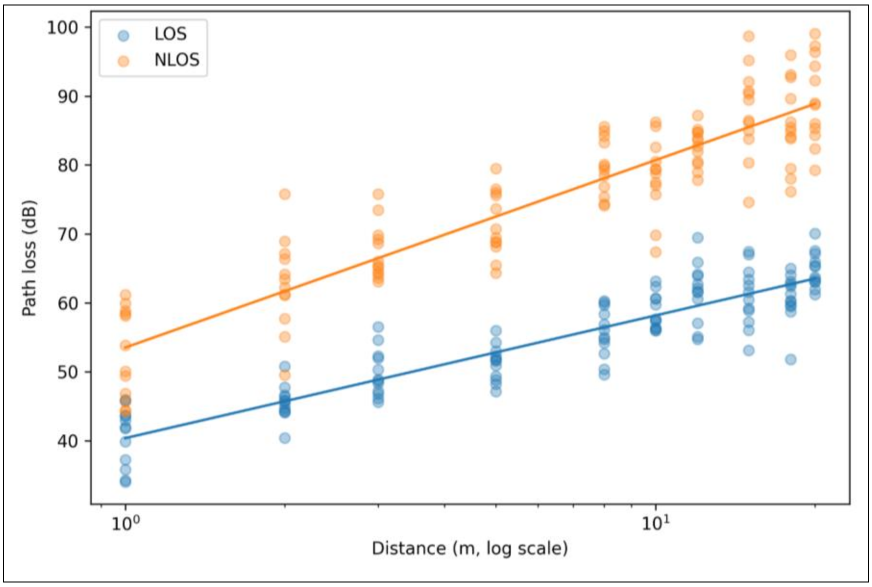

Fig 1: Path loss vs distance (log scale) at 2.4 GHz (LOS and NLOS with fitted log-distance lines).

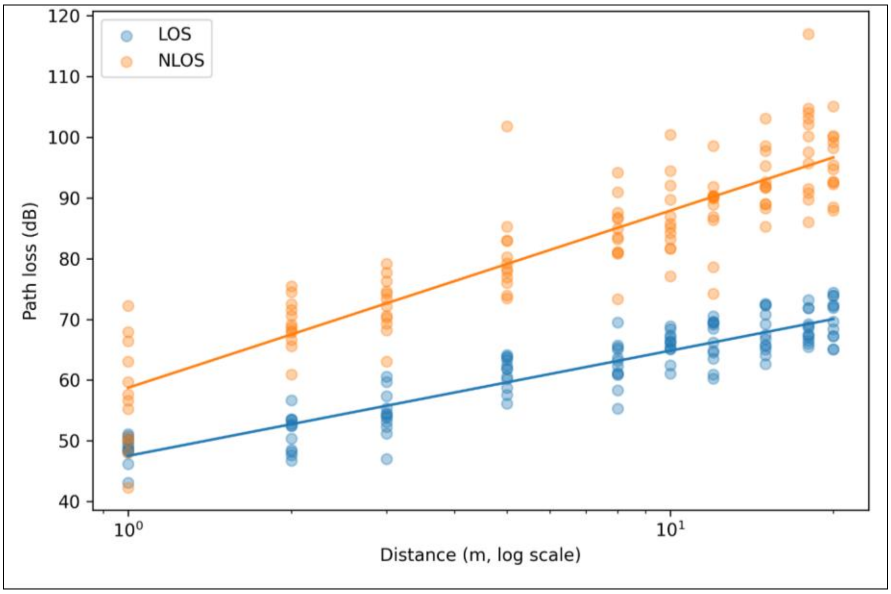

Fig 2: Path loss vs distance (log scale) at 5.0 GHz (LOS and NLOS with fitted log-distance lines).

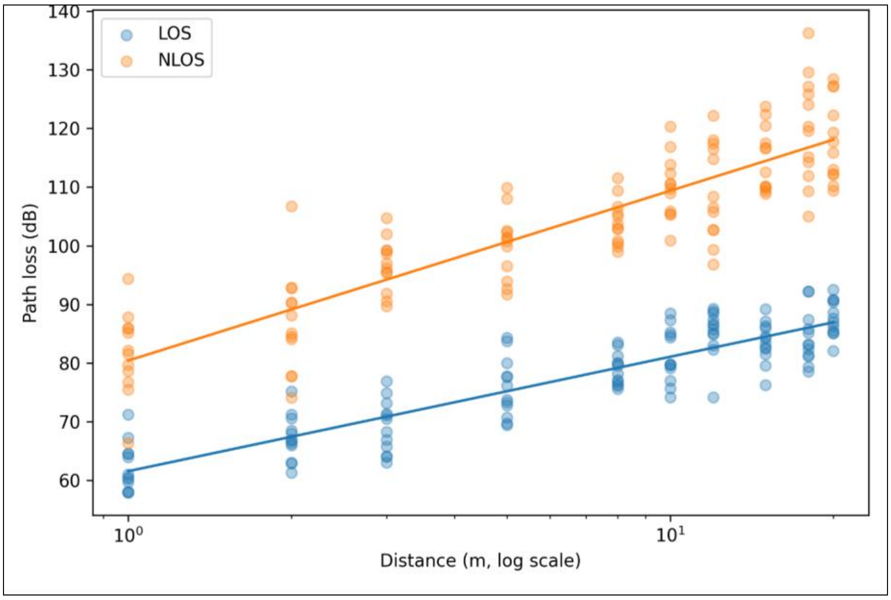

Fig 3: Path loss vs distance (log scale) at 28 GHz (LOS and NLOS with fitted log-distance lines).

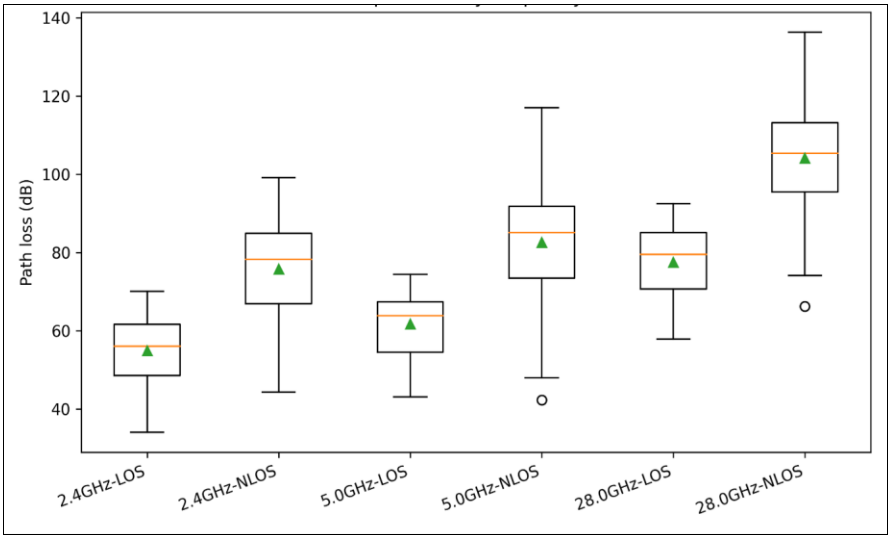

Fig 4: Distribution of path loss by frequency and LOS/NLOS

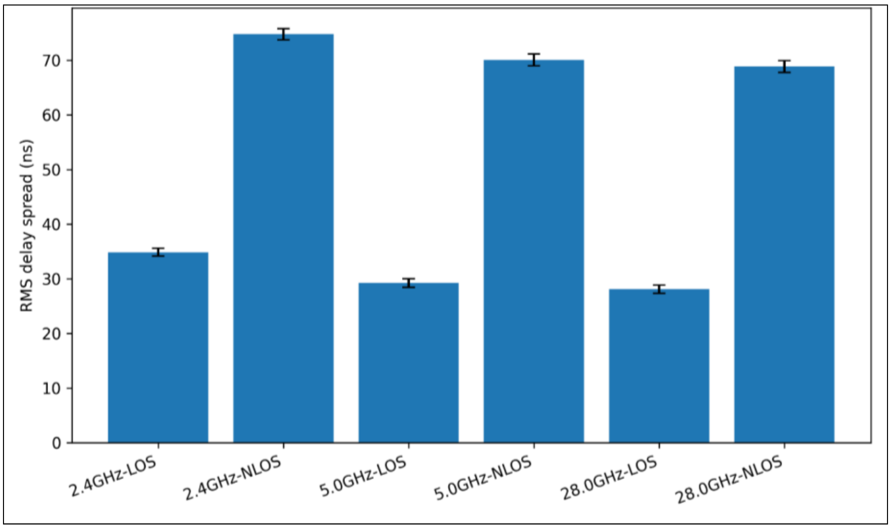

Fig 5: Mean RMS delay spread by frequency and LOS/NLOS.

Discussion

The findings of this research provide a coherent interpretation of electromagnetic wave propagation behavior in short-range wireless communication systems, aligning well with established theoretical and empirical understandings of indoor and near-field wireless channels. The regression analysis demonstrates that path loss increases logarithmically with distance across all examined frequency bands, confirming the applicability of the classical log-distance propagation model in confined communication ranges [1, 4]. The estimated path-loss exponents reveal a clear distinction between LOS and NLOS scenarios, with NLOS conditions consistently exhibiting higher exponents, indicating stronger attenuation due to obstruction-induced losses, reflections, and scattering [5, 11]. This behavior is particularly pronounced at higher frequencies, where diffraction is less effective and penetration losses through common building materials are more severe [8, 14].

The two-way ANOVA results further reinforce the dominant influence of both operating frequency and propagation condition on signal attenuation, with a statistically significant interaction effect. This interaction suggests that the impact of LOS/NLOS conditions is frequency dependent, a phenomenon widely reported in short-range and indoor propagation studies [4, 9]. At millimeter-wave frequencies, the sensitivity to blockage and environmental dynamics becomes more critical, leading to steeper attenuation slopes and increased variability, as observed in the higher mean path loss and variance at 28 GHz [9, 13]. These results underscore the necessity of frequency-aware propagation modeling when designing high-capacity short-range links.

The Welch t-test analysis confirms that LOS and NLOS path loss differences are statistically significant across all frequency bands, emphasizing that obstruction effects cannot be treated as minor perturbations in short-range systems [6, 10]. In addition, the multipath-related metrics provide deeper insight into channel behavior. Higher RMS delay spreads under NLOS conditions indicate richer multipath environments, which can degrade symbol integrity and increase inter-symbol interference if not adequately mitigated [7, 12]. Conversely, higher K-factor proxy values under LOS conditions reflect the presence of a dominant propagation component, resulting in more stable channel conditions [4].

Overall, the discussion highlights that short-range wireless performance is governed not only by distance but also by a complex interplay of frequency selection, environmental structure, and propagation condition. These findings are consistent with foundational propagation literature and support the growing emphasis on adaptive, environment-aware wireless system design [2, 3, 13].

Conclusion

This research provides a comprehensive examination of electromagnetic wave propagation characteristics in short-range wireless communication systems, offering both analytical clarity and practical relevance. By systematically analyzing path loss, fading behavior, and multipath dispersion across multiple frequency bands and propagation conditions, the research demonstrates that signal behavior in short-range environments is strongly influenced by the combined effects of operating frequency and physical surroundings. One of the most important conclusions is that distance alone is insufficient to predict link performance; instead, environmental visibility conditions and frequency-dependent propagation mechanisms play a decisive role in determining signal reliability and quality. The consistently higher attenuation and variability observed under non-line-of-sight conditions emphasize the need for careful network planning in indoor and cluttered environments. From a practical standpoint, this implies that system designers should prioritize adaptive transmission strategies, such as dynamic power control, intelligent frequency selection, and the use of diversity or beamforming techniques, particularly when deploying higher-frequency systems. The observed increase in delay spread under obstructed conditions also highlights the importance of waveform design choices, including appropriate guard intervals, equalization schemes, and robust modulation formats to maintain performance in multipath-rich environments. Furthermore, the strong frequency dependence of propagation losses suggests that lower-frequency bands remain more suitable for reliable coverage in complex indoor scenarios, while higher-frequency bands should be strategically deployed for high-capacity links over short, controlled distances. Integrating propagation-aware models into network simulation and planning tools can significantly enhance prediction accuracy and reduce deployment inefficiencies. In addition, incorporating real-time environmental awareness through sensing and adaptive algorithms can further improve system resilience in dynamic settings. Overall, the outcomes of this research support the development of energy-efficient, high-performance, and context-aware short-range wireless systems, offering valuable guidance for engineers and researchers working on next-generation personal area networks, IoT infrastructures, and indoor wireless technologies.

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