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Microwave Link Budget, Rain Attenuation, and the Role of Satellite Laser Communications in Future Networks

Yuxuan Qi

School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, China
Qiyx20041129@icloud.com

Abstract. Microwave and millimeter-wave backhaul links play a vital role in modern communication networks by enabling high-capacity data transmission over distances ranging from hundreds of meters to several kilometers. These systems typically operate in high-frequency bands above 10 GHz, where a wider bandwidth is available. While such frequencies support compact antenna design and reduced interference through highly directional beams, they are also more susceptible to propagation losses and atmospheric effects, particularly rain attenuation. This paper presents a systematic analysis of microwave link budget design and rain attenuation mechanisms. Fundamental link budget calculation methods are introduced based on free-space propagation models, along with key system gain and loss factors. Rain attenuation is examined through established modeling approaches, and its impact on link reliability is analyzed under different environmental conditions. In addition, regional characteristics and advanced applications, including rainfall inversion and radar correction, are discussed to demonstrate the broader relevance of microwave link analysis. Furthermore, the study explores satellite laser communication as an emerging complementary technology. Compared with conventional microwave systems, laser communication offers significantly higher data rates, larger bandwidth, and enhanced security. However, it is more sensitive to atmospheric conditions. Therefore, a hybrid communication framework combining microwave and laser technologies is considered to improve overall system robustness and performance. The results indicate that accurate link budget modeling and effective mitigation of rain attenuation are essential for reliable high-frequency communication. Moreover, the integration of microwave and laser communication technologies is expected to play a key role in future satellite-terrestrial networks, particularly in the development of 6G systems.

Keywords: Microwave link budget, Rain attenuation modeling, Millimeter-wave backhaul, Satellite laser communication, 6G integrated networks

1. Introduction

Microwave communication has long underpinned terrestrial and satellite systems, supporting mobile backhaul, fixed point-to-point links, and satellite connections. With 5G deployment accelerating and 6G on the horizon, microwave and millimeter-wave bands are increasingly vital for high-bandwidth low-latency transmission [1]. The International Telecommunication Union (ITU) designates frequencies above 24 GHz as critical for meeting surging data demands [2]. Link budget analysis remains a cornerstone of wireless system design: it quantifies how transmitted power, antenna gains, propagation losses, and system margins interact [3]. While free-space path loss is at lower frequencies, rain attenuation becomes a major impairment above 10 GHz, where signals are highly sensitive to atmospheric conditions [4].

To model this, ITU-R P.838 provides an empirical framework linking specific attenuation to rainfall intensity via region-dependent coefficients [5]. Yet global models often lack accuracy due to spatial and temporal variability, necessitating regional calibration [6]. Advanced models like the SC-EXCELL model improve predictions by simulating rain cells and capturing attenuation distributions more realistically for terrestrial links [7]. In parallel, satellite laser communication is emerging as a powerful complement to traditional microwave systems. Operating at optical wavelengths, it offers substantially higher bandwidth, enhanced directivity, and improved security performance, making it well-suited for 6G satellite–terrestrial integration [8]. Nevertheless, practical challenges such as beam acquisition, tracking precision, and atmospheric turbulence still constrain its large-scale deployment. This paper focuses on link budget analysis and rain attenuation modeling for microwave communication systems, while also extending the discussion to the integration of satellite laser communication technologies in next-generation networks.

2. Theoretical basis of microwave link budget

2.1. Free-space propagation model

The free-space propagation model describes the fundamental relationship between transmitted and received signals under ideal line-of-sight (LOS) conditions, without considering environmental effects such as reflection, diffraction, or atmospheric attenuation. The received power in a free-space channel can be expressed using the Friis transmission equation:

$$P_r = P_t + G_t + G_r - L_{fs} \tag{1}$$

where P_t denotes the transmit power (dBm), G_t and G_r represent the transmit and receive antenna gains (dBi), respectively, and L_{fs} is the free-space path loss (dB). The free-space path loss can be further calculated as:

$$L_{fs}(dB) = 92.45 + 20\log_{10}(d_{km}) + 20\log_{10}(f_{GHz}) \tag{2}$$

Where d is the transmission distance in kilometers and f is the carrier frequency in GHz.

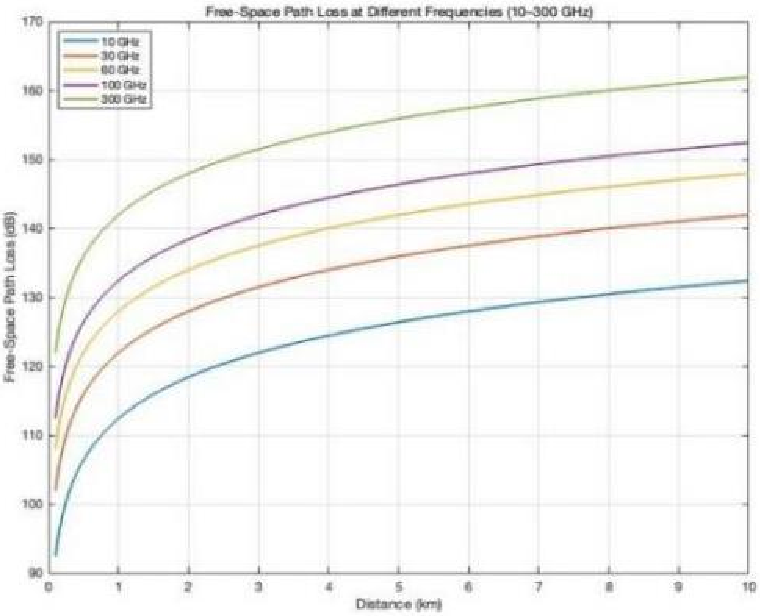

Figure 1. Free-space path loss at different frequencies (10–300 GHz) as a function of distance

Figure 1 shows the variation of free-space path loss with distance for different frequency bands ranging from 10 GHz to 300 GHz. It can be observed that the path loss increases monotonically with distance due to the logarithmic relationship between distance and attenuation.

In addition, higher frequency signals experience significantly greater path loss compared to lower frequency signals at the same distance. For instance, the attenuation at 300 GHz is considerably higher than that at 10 GHz, which reflects the strong frequency dependence of free-space propagation loss.

Another important observation is that free-space path loss increases logarithmically with distance. As a result, the incremental increase in attenuation appears less pronounced at longer transmission distances. Furthermore, the impact of frequency on propagation loss highlights a key design trade-off in modern communication systems. While higher frequencies enable larger bandwidth and higher data rates, they also lead to increased propagation losses, making accurate link budget analysis essential.

In addition to free-space loss, practical communication systems must also consider other impairments such as atmospheric absorption and rain attenuation. These effects will be further analyzed in subsequent sections.

2.2. System gains and loss factors

In practical wireless communication systems, the received signal power is influenced not only by free-space propagation loss but also by various additional gain and loss factors. These factors must be carefully considered in link budget analysis to ensure accurate system performance evaluation [3].

The main loss components include feeder loss, polarization mismatch loss, building penetration loss, and fading margin. Feeder loss is typically caused by transmission lines and connectors and usually ranges from 2 to 3 dB in practical systems. Building penetration loss becomes significant when signals propagate from outdoor base stations to indoor users, and it can reach approximately 15–20 dB depending on the construction materials and frequency band.

Polarization mismatch loss occurs when the polarization of the transmitted and received signals is not perfectly aligned, leading to additional signal degradation. Furthermore, a fading margin is introduced to compensate for large-scale and small-scale fading effects caused by obstacles, shadowing, and multipath propagation. This margin is essential to guarantee a certain level of link reliability under varying environmental conditions.

In addition to losses, system gains also play an important role. The selection of antenna type, gain, and orientation directly affects the effective isotropic radiated power (EIRP), which determines the strength of the transmitted signal in a given direction. Therefore, proper system design requires a balanced consideration of both gain enhancement and loss mitigation.

2.3. Link margin calculation

The maximum allowable path loss (MAPL) defines the upper limit of propagation loss that a communication link can tolerate while still maintaining reliable performance. It is a key parameter in link budget design and directly determines the achievable coverage range of the system [3].

The MAPL can be expressed as:

$$\mathrm{MAPL}=\mathrm{EIRP}-\mathrm{S}_{\mathrm{min}}+\mathrm{G}_{\mathrm{r}}-\mathrm{L}_{\mathrm{m}} \tag{3}$$

where EIRP represents the effective isotropic radiated power of the transmitter, $\mathrm{S}_{\mathrm{min}}$ is the minimum receiver sensitivity, G_{r} is the receive antenna gain, and L_{m} denotes the total system margin.

The system margin L_{m} accounts for various additional losses and uncertainties in practical environments. These typically include rain attenuation, shadow fading margin, penetration loss, and other implementation-related losses. Among these factors, rain attenuation becomes increasingly significant at higher frequencies, especially in millimeter-wave bands, where it can severely limit link availability.

Furthermore, shadow fading margin is introduced to ensure reliable communication under large-scale environmental variations, while additional margins may be required to compensate for hardware imperfections and interference effects. Therefore, the accurate estimation of L_{m} is essential for achieving a balance between system reliability and coverage efficiency.

From an engineering perspective, MAPL serves as a bridge between theoretical analysis and practical deployment. A larger MAPL generally indicates a longer achievable transmission distance; however, it also requires stricter system design constraints, such as higher transmit power or improved antenna performance.

3. Rain attenuation mechanism and modeling

3.1. Electromagnetic impact of raindrops

Raindrops affect electromagnetic wave propagation primarily through two mechanisms: scattering and absorption. When radio waves propagate through rain, part of the energy is absorbed by water molecules, while another portion is scattered in different directions, resulting in a reduction of the received signal power.

The severity of this effect strongly depends on the relationship between the wavelength of the electromagnetic wave and the size of raindrops. At lower frequencies, where the wavelength is much larger than the raindrop diameter, the impact of rain is relatively small. However, as the frequency increases into the microwave and millimeter-wave bands, the wavelength becomes comparable to the size of raindrops, leading to significantly enhanced scattering and absorption effects [4].

As a result, rain attenuation increases rapidly with frequency and becomes a dominant propagation impairment above 10 GHz. Experimental studies have shown that under heavy rainfall conditions, particularly in tropical regions, rain attenuation can exceed 10 dB/km, which severely limits the transmission distance and link availability [4].

From a physical perspective, this phenomenon can be explained by the interaction between electromagnetic waves and dielectric particles (raindrops), where resonance and energy dissipation effects become more pronounced at higher frequencies. Therefore, accurate modeling of rain attenuation is essential for reliable system design in high-frequency communication systems.

3.2. ITU-R models and applications

The ITU-R P.838 recommendation provides a widely adopted empirical model to estimate rain attenuation in microwave and millimeter-wave communication systems [5]. The specific attenuation caused by rain can be expressed as:

$$\gamma_R = kR^{\alpha} \tag{4}$$

where γ_R is the specific attenuation (dB/km), R represents the rainfall rate (mm/h), and k and α are coefficients that depend on frequency and signal polarization.

The total rain attenuation over a transmission path of length d can be calculated as:

$$A_{rain} = \gamma_R \cdot d \tag{5}$$

This model shows that rain attenuation increases nonlinearly with rainfall intensity, indicating that severe weather conditions can significantly degrade communication performance. In high-frequency bands such as the E-band (70–80 GHz), attenuation can reach 30–40 dB under heavy rainfall conditions, which poses a major challenge for reliable link design [5].

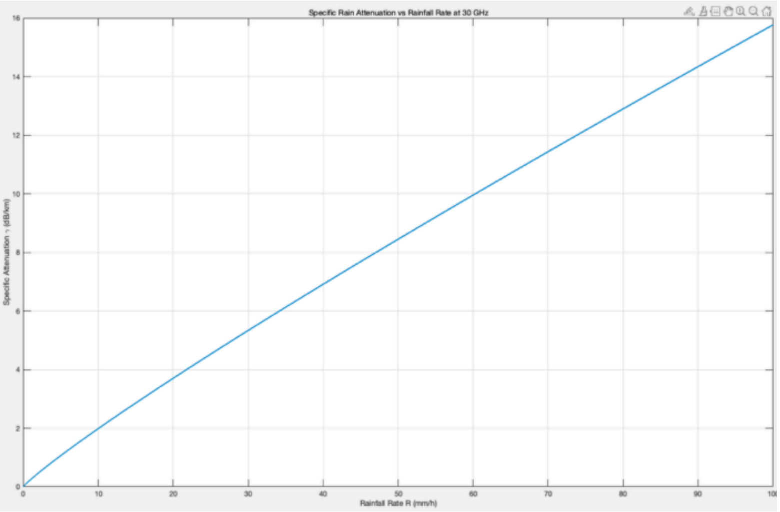

Figure 2. The specific rain attenuation vs rainfall rate at 30Ghz

Figure 2 shows the variation of specific rain attenuation with rainfall rate at 30 GHz. It can be observed that the attenuation increases nonlinearly with rainfall intensity. At lower rainfall rates, the increase in attenuation is relatively gradual, while at higher rainfall rates, the attenuation grows more rapidly, indicating a stronger sensitivity to heavy precipitation.

This nonlinear behavior is consistent with the power-law relationship between attenuation and rainfall rate, where the exponent parameter leads to an accelerated increase at higher values of rainfall intensity. As the rainfall rate exceeds moderate levels, the attenuation rises significantly, which may result in severe degradation of signal quality.

The results demonstrate that in high-frequency communication systems, especially in millimeter-wave bands, heavy rainfall conditions can become a dominant limiting factor. Therefore, rain attenuation must be carefully considered in link budget design, and sufficient fade margins are required to ensure reliable communication performance. This trend highlights the importance of accurate rain attenuation modeling in the design of high-capacity microwave and E-band communication systems.

3.3. Advanced models: SC-EXCELL and regional adaptations

Although the ITU-R model provides a convenient and widely used approach, it is fundamentally empirical and may not fully capture the spatial variability of rainfall. To address this limitation, more advanced statistical models have been developed.

The SC-EXCELL model introduces the concept of synthetic rain cells with exponential decay to represent the spatial distribution of rainfall intensity. By modeling the rainfield as a collection of such cells, the SC-EXCELL approach enables the prediction of the probability distribution of rain attenuation, rather than only deterministic values. Moreover, it does not require calibration using local measurement data, which enhances its applicability across different regions [8].

In addition to statistical modeling, rainfall inversion based on commercial microwave links has recently emerged as a novel technique. By analyzing signal attenuation along communication links, it is possible to estimate rainfall intensity in real time. For example, short-link inversion models have been proposed to reduce the overestimation problem associated with traditional power-law relationships. These methods not only improve the accuracy of link design but also provide valuable data for meteorological monitoring and environmental sensing.

4. Applications of link budget

Link budget analysis plays a critical role in the design and optimization of modern communication systems. It provides a quantitative framework to evaluate system performance under different propagation conditions and directly influences coverage planning, reliability, and deployment cost.

4.1. Terrestrial point-to-point microwave

Terrestrial point-to-point microwave links are widely deployed in both rural and urban backhaul scenarios, particularly in areas where fiber deployment is economically or physically impractical. In such systems, link budget analysis is essential for determining the maximum transmission distance and ensuring reliable communication.

For example, in 3.5 GHz 5G systems, path loss plays a dominant role in defining the achievable cell radius and base station density [1]. As the path loss increases with distance, higher transmit power or antenna gain is required to maintain sufficient signal strength. This directly impacts network planning, as shorter link distances result in a higher number of base stations and increased deployment cost.

Therefore, accurate link budget estimation is crucial for balancing coverage performance and infrastructure investment in terrestrial microwave networks.

4.2. Satellite communication

In satellite communication systems, rain attenuation becomes a critical limiting factor, especially at higher frequency bands such as Ka-band and above. Due to the long propagation distance and the presence of atmospheric layers, signal attenuation can significantly affect link availability and quality.

Path attenuation estimation under complex meteorological conditions has shown that rainfall events can drastically reduce system availability [4]. In severe weather conditions, the signal may experience deep fading, leading to temporary communication outages.

To address this issue, advanced techniques such as tomographic reconstruction of attenuation fields have been proposed. These methods aim to improve the accuracy of attenuation prediction and enable adaptive system design, thereby enhancing the robustness of satellite communication links.

4.3. 5G/6G backhaul

With the rapid development of 5G and future 6G networks, E-band microwave links have become an important solution for high-capacity backhaul. Although free-space path loss and rain attenuation are both significant at these high frequencies, E-band systems can still achieve multi-gigabit data rates when sufficient fade margins are incorporated into the link budget [2].

However, the strong sensitivity of E-band signals to rainfall requires accurate attenuation modeling. Standardization of rain attenuation models, particularly in regions with diverse climatic conditions such as China, is essential for reliable system deployment [5].

Overall, link budget analysis in high-frequency backhaul systems must carefully consider both propagation loss and environmental factors to ensure high reliability and performance.

5. Mitigation of rain attenuation and beyond

Power Control: Dynamic adjustment of transmit power is a straightforward method to maintain link reliability. LTE and 5G systems use uplink power control to compensate for fading, and similar mechanisms are applicable to microwave backhaul [3].

Adaptive Modulation and Coding: Adaptive modulation is a key technique in E-band microwave systems. It enables the link to downgrade modulation order under heavy rain while maintaining connectivity [2].

Frequency and Site Diversity: Site diversity, where geographically separated stations provide redundancy, is effective in regions with localized rainfall. Frequency diversity, combining lower and higher frequency bands, enhances availability [5].

Hybrid Techniques: Terahertz links under rainfall require hybrid designs. Combining optical and microwave paths provides resilience against severe rain fade by switching traffic to less affected channels [8].

Laser–Microwave Cooperation: Recent studies emphasize that laser and microwave links should be integrated into future satellite–terrestrial networks [7]. Laser communication provides extremely high capacity but is highly sensitive to atmospheric conditions such as turbulence, cloud cover, and rain. In contrast, microwave links offer lower capacity but maintain higher reliability under adverse weather conditions. The effective capacity of a hybrid communication system can be expressed as:

$$C_{total}=C_{laser}(1-P_{out})+C_{RF}\cdot P_{out} \tag{6}$$

where C_{laser} is the capacity of the laser link, C_{RF} is the microwave link capacity, and P_{out} represents the outage probability of the laser link. This expression shows that even when the laser link becomes unavailable due to atmospheric conditions, the microwave link can sustain system performance. Therefore, the hybrid architecture significantly improves overall system robustness.

Figure 3 illustrates the conceptual architecture of a hybrid laser–microwave communication system. It demonstrates how traffic can be dynamically switched between optical and microwave channels to maintain both high throughput and reliable connectivity.

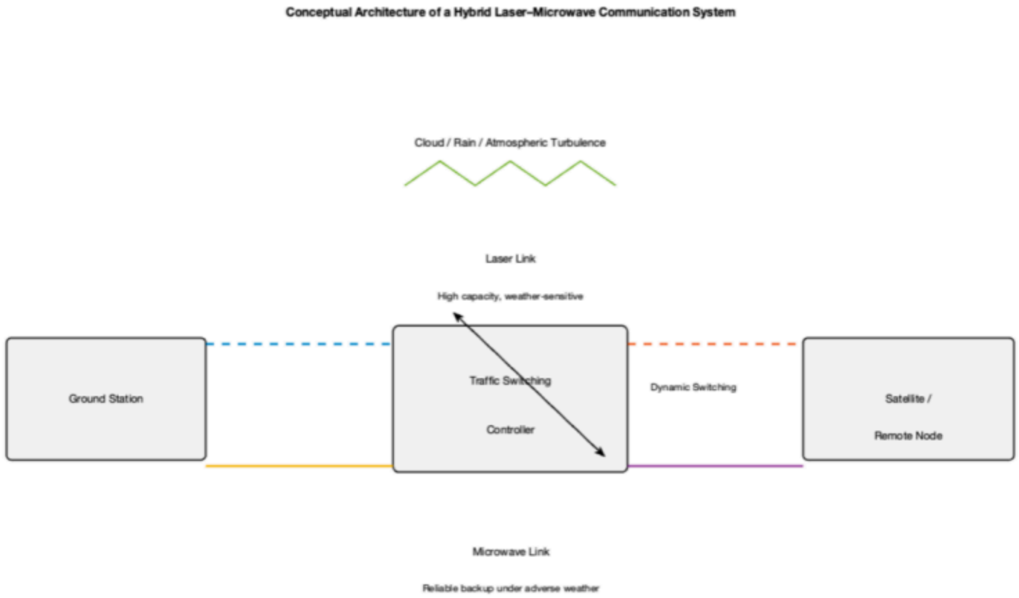

Figure 3. Conceptual architecture of a hybrid laser–microwave communication system

Table 1. Link budget comparison at different frequencies under identical conditions

Frequency(GHz)	FSPL(dB)	Rain Attenuation(dB)	Total Loss(dB)
10	122.4	0.3	122.7
28	135.4	1.04	136.4
60	142.0	5.5	147.5
80	145.0	9.8	154.8

Table 1 compares link budget performance at different frequency bands under the same transmission distance and rainfall conditions. It can be observed that both free-space path loss and rain attenuation increase with frequency. In particular, rain attenuation becomes a dominant factor at higher frequencies, significantly increasing the total path loss. This demonstrates that high-frequency systems require larger fade margins to maintain reliable communication.

6. Conclusion

This paper presented a comprehensive analysis of microwave link budget design and rain attenuation mechanisms in modern wireless communication systems. The study first introduced the fundamental principles of free-space propagation and link budget calculation, highlighting the importance of parameters such as transmit power, antenna gain, and system margins. It was shown that accurate estimation of path loss is essential for determining system coverage and ensuring reliable communication performance.

The impact of rain attenuation was then investigated in detail. The analysis demonstrated that rain-induced signal degradation becomes increasingly severe at higher frequencies, particularly in microwave and millimeter-wave bands. Standardized models such as the ITU-R P.838 recommendation provide a practical approach for predicting attenuation based on rainfall intensity. However, their limitations in capturing regional variations were also discussed, which motivates the use of more advanced models such as the SC-EXCELL approach.

Furthermore, this paper explored various mitigation techniques, including power control, adaptive modulation, diversity schemes, and hybrid communication strategies. Among these, the integration of microwave and laser communication systems was identified as a promising solution for future high-capacity networks. While laser communication offers ultra-high data rates, microwave links ensure reliability under adverse weather conditions, making their combination highly effective.

Despite these contributions, this study still has some limitations. The analysis is primarily based on theoretical models and simplified assumptions, without incorporating large-scale real-world measurement data. Future research can focus on improving model accuracy using experimental validation and developing adaptive systems that dynamically respond to environmental changes.

In conclusion, the results indicate that reliable high-frequency communication systems require both accurate link budget modeling and effective mitigation of environmental effects. The integration of microwave and laser communication technologies is expected to play a key role in future 6G satellite–terrestrial networks, enabling both high capacity and robust performance.

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