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Rain Attenuation Mitigation Techniques in Terahertz-Band Communication for Wireless Data Transmission

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Abstract

The increasing demand for higher wireless data rates has directed attention towards terahertz-band (0.1 to 10THz) communication, which offers substantial transmission bandwidths capable of supporting terabit-per-second (Tbps) links. However, atmospheric conditions, particularly rain, significantly affect the higher frequencies in this band, causing substantial signal attenuation. This paper explores various rain attenuation mitigation techniques essential for maintaining the quality of THz-band communication. Techniques such as amplification, equalization, forward error correction, and diversity methods are analyzed for their effectiveness, advantages, and limitations. Additionally, adaptive coding and modulation, site diversity, power control, time diversity, and reconfigurable antenna patterns are evaluated to provide a comprehensive approach to mitigating rain-induced signal degradation. The paper also compares empirical and semi-empirical models, including ITU-R, Mie scattering, and Liebe's models, which predict rain attenuation accurately. By deploying these mitigation strategies, it is possible to achieve reliable and high-quality THz-band communication even under adverse weather conditions.

Keywords: Attenuation, Mitigation, Terahertz, Frequency, Techniques

Techniques d'atténuation des effets de la pluie dans les communications en bande térahertz pour la transmission de données sans fil

Résumé

La demande croissante en débits de données sans fil plus élevés a orienté l'attention vers les communications en bande térahertz (0,1 à 10 THz), offrant des largeurs de bande de transmission considérables capables de supporter des liaisons à plusieurs térabits par seconde (Tbps). Cependant, les conditions atmosphériques, en particulier la pluie, affectent significativement les fréquences élevées de cette bande, provoquant une atténuation importante du signal. Cet article explore diverses techniques d'atténuation des effets de la pluie, essentielles pour maintenir la qualité des communications en bande THz. Des techniques telles que l'amplification, l'égalisation, la correction d'erreur anticipée (FEC) et les méthodes de diversité sont analysées pour leur efficacité, leurs avantages et leurs limites. De plus, des approches telles que la modulation et codage adaptatifs, la diversité de site, le contrôle de puissance, la diversité temporelle et les motifs d'antenne reconfigurables sont évaluées afin de proposer une stratégie complète pour atténuer la dégradation du signal causée par la pluie. L'article compare également des modèles empiriques et semi-empiriques, notamment ceux de l'UIT-R, de la diffusion de Mie et de Liebe, qui prédisent avec précision l'atténuation due à la pluie. En déployant ces stratégies d'atténuation, il est possible d'assurer des communications fiables et de haute qualité en bande THz, même dans des conditions météorologiques défavorables.

Rain Attenuation Mitigation Techniques in Terahertz-Band Communication for Wireless Data Transmission

Mots-clés : Atténuation, Mitigation, Térahertz, Fréquence, Techniques

تقنيات التخفيف من تداخل المطر في الاتصالات ضمن نطاق التيراهيرتز لنقل البيانات اللاسلكية.

إن الطلب المتزايد على معدلات أعلى لنقل البيانات اللاسلكية قد وجّه الأنظار نحو الاتصالات ضمن نطاق التيراهيرتز (0.1 إلى 10 تيراهيرتز)، والذي يوفر نطاقات ترددية واسعة قادرة على دعم سرعات نقل تصل إلى تيرابت في الثانية (Tbps).ومع ذلك، فإن الظروف الجوية، وخصوصًا الأمطار، تؤثر بشكل كبير على الترددات العليا في هذا النطاق، مما يؤدي إلى تدهور ملحوظ في الإشارة. تستعرض هذه الورقة البحثية مجموعة من تقنيات التخفيف من تأثير تداخل الأمطار، والتي تُعد ضرورية للحفاظ على جودة الاتصالات في نطاق التيراهيرتز.

تشمل التقنيات التي تم تحليلها: التضخيم، والمعادلة، وتصحيح الخطأ المتقدم، وطرق التنويع، حيث تم تقييم فعاليتها ومزاياها وقيودها. بالإضافة إلى ذلك، تم تقييم تقنيات مثل التكويد والتعديل التكيفي، وتنويع المواقع، والتحكم في الطاقة، وتنويع الزمن، وأنماط الهوائيات القابلة لإعادة التكوين، لتقديم نهج شامل للتعامل مع تدهور الإشارة الناتج عن الأمطار. كما تُجري الورقة مقارنة بين النماذج التجريبية وشبه التجريبية، بما في ذلك نموذج الاتحاد الدولي للاتصالات (ITU-R)، ونموذج تشتت مي، ونموذج ليب، والتي تتنبأ بتداخل المطر بدقة.ومن خلال تطبيق هذه الاستراتيجيات، يمكن تحقيق اتصالات موثوقة وعالية الجودة في نطاق التيراهيرتز حتى في ظل الظروف الجوية القاسية.

الكلمات المفتاحية: **التوهين، التخفيف، التيراهيرتز، التردد، التقنيات**

Introduction

Terahertz-band (0.1 to 10THz) communication is envisioned as a potential key wireless technology to satisfy the need for much higher wireless data rates (Federici and Moeller, 2010; Kurner and Priebe, 2014). The THz band supports huge transmission bandwidths, which range from almost 10THz for distances below one meter, to multiple transmission windows, each ten to hundreds of GHz wide, for distances on the order of a few tens of meters. Nevertheless, this very large bandwidth comes at the cost of a very high propagation loss (Jornet and Akyildiz, 2011). For many decades, the lack of compact high-power signal sources and high-sensitivity detectors has hampered the use of the THz band for any application beyond sensing. However, recent advancements with different technologies are finally closing the so-called THz gap.

THz-band communication can address two relevant challenges first; THz-band frequencies (0.1 to 10THz) remain almost completely unutilized for communication. Second, the THz band supports huge transmission bandwidths (from hundreds of GHz up to a few THz, depending on the transmission distance and medium composition). This can enable, for the first time, wireless Terabit-per-second (Tbps) links and opens the door to transformative applications, such as in-air big-data sharing for real-time monitoring, decision and actuation with unmanned aerial vehicle networks.

However, the higher frequencies are considerably affected by rain-fall. Rain is a natural phenomenon that attenuates the propagating signal at microwave and millimeter-wave frequencies. Therefore, it is necessary to mitigate rain attenuation to ensure the quality of microwave and millimeter-wave links. To this end, dynamic attenuation mitigation methods are implemented alongside attenuation prediction models that can predict the projected attenuation of the links. Multiple studies have been conducted on this issue worldwide by different researchers. Studies on rain attenuation are used in geographically distributed locations to analyze and develop a rain attenuation model applicable over a wide frequency range, particularly radio frequencies over

approximately 30 GHz for 5G and beyond network applications (Samuel *et al*., 2021). Rainfall intensity, frequency of operation, and link distance are significant parameters that determine rain attenuation. Various rain attenuation prediction models have mapped the correlation between rainfall intensity, path length, and frequencies with rain attenuation. An increment in rainfall rate increases the chance of interfering probability with radio waves (Shayea *et al*. 2018). In some studies, attenuation because of rain was reported at even lower frequencies, such as 5 GHz (Goddard and Thurai, 1997) and 7 GHz (Moupfouma, 1984). Many rain attenuation models have been proposed in the literature, and researchers have attempted to improve existing models to fit with local climatic conditions (Al-Saman *et al*., 2019). It was shown that rain attenuation could reduce the throughput of a link compared to sunny weather conditions (Hilt, 2019). By deploying an appropriate rain attenuation model, even in the rain, a terrestrial link's throughput can be kept unchanged compared to a case without deploying any fade mitigation technique (FMT) and with the condition that other parts are usually working. FMT might be attained in several ways, such as power control, modulation techniques, adaptive waveform, and diversity techniques. If we do not consider power control of FMT owing to rain attenuation, then it is not possible to avoid overestimating or underestimating a transmission system's power
.

Rain Attenuation Mitigation Techniques

The key objective for implementing the Fade Mitigation Technique (FMT) system should be the avoidance of static channel parameters and the design of adaptive systems that compensate for channel effects only when required, while at the same time providing the desired minimum quality of service (QoS) under clear-sky conditions.

Various techniques are employed to mitigate this problem. Below are some commonly used techniques, explained with relevant equations, the merits and demerits of each technique are discussed, followed by a suggestion for the best technique.

Amplification:

Amplification involves boosting the signal strength using amplifiers at various points in the communication link.

The gain G of an amplifier is given in equation 1

$$G = 10log_{10}\frac{P_{out}}{P_{in}} \quad (1)$$

Where P_{out} is the output power and P_{in} is the input power

The merits;

- It is effective over long distances. Amplifiers can boost signals to travel longer distances without degradation.
- It is widely used in various applications; found in both wired and wireless communication system.

Demerits:

- Noise amplification: amplifiers also boost noise along with the signal.
- Nonlinear distortion: at high power levels, amplifiers may introduce nonlinear distortion.

Equalization:

Equalization involves using an equalizer to compensate for the signal distortion caused by the transmission medium.

The transfer function of an equalizer $H_{eq}(f)$ is designed to be the inverse of the channel transfer function $H_{ch}(f)$: the transfer function is given in equation 2

$$H_{eq}(f) = \frac{1}{H_{ch}(f)} \quad (2)$$

Merits:

- Compensation for multipath fading: effective in mitigating the effects of multipath fading and inter-symbol interference.

Enhances signal quality; improves the overall signal quality.

Demerits:

Complexity: design and implementation can be complex

➢ Adaptation required; may require continuous adaptation in a varying channel

Forward Error Correction (FEC)

FEC adds redundant data to the transmitted information, allowing the receiver to detect and correct errors without re-transmission, and is given in equation 3

$$G_c = 10log_{10}\frac{SNR_{uncoded}}{SNR_{coded}} \qquad (3)$$

Where $SNR_{uncoded}$ is the signal –to- noise without coding and SNR_{coded} is the signal-to-noise ratio with coding.

Merits:

Improves reliability: Enhances the reliability of data transmission.

No need for re-transmission: Errors can be corrected at the receiver without needing re-transmission.

Demerits:

Increased bandwidth: Requires additional bandwidth for the redundant data.

Processing delay: Introduces processing delay due to encoding and decoding.

Diversity Techniques

Diversity techniques involve using multiple signal paths to improve the robustness of the received signal.

For maximal-ratio combining (MRC), the combined signal-to-noise ratio (SNR) γ is the sum of the SNRs of the individual branches, and this is given in equation 4

$$\gamma = {}_{i=1}^{N}\gamma_i \qquad (4)$$

Where γ_i is the SNR of the i -th branch.

Merits:

Reduces fading effects; effectively reduces the impact of fading and improves reliability.

No additional power required; utilizes existing power more efficiently without needing extra power

Demerits:

Resource intensive; requires multiple antennas or paths, which may not be feasible in all scenarios.

Increased complexity; adds complexity to the system design and implementation

Some of the Rain Attenuation Mitigation Techniques Used by other Researchers

Frequency diversity (FD): This was used by Athanasios D. Panagopoulos *et al*., (2004); (Gremont, 2003). He used frequency domain separation (in closed loop control) of propagation factors based on the fact that lower frequency components of the attenuation power spectrum are associated with gaseous absorption, mid-frequency with clouds and rain, and higher frequencies with scintillations. This makes it possible to achieve the necessary separation through appropriate filtering. This is similar to one of the methods suggested by Gremont B. C. (Panagopoulos *et al*., 2004), which he adjudged to be the most precise method in principle (Gremont, 2003). Frequency scaling and other methods for the detection or estimation of fades are usually incorporated into a control loop, like the one obtained from (Panagopoulos *et al*., 2004).

Adaptive coding and modulation (ACM) could be used by the system by implementing, for instance, the most efficient coding rate (e.g., QPSK 9/10 with a spectral efficiency of 1.788612 information bits per symbol, an ideal Es/No of 6.42 dB, and a threshold Es/No of 7.42 dB) (Maurolagoitia *et al*., 2006). When the link threshold is affected by rain events, the link would then switch to a less efficient but more robust coding rate, thereby adapting to the variations of the rain attenuation.

Site diversity (SD): FMT is based on the premise that the probability of attenuation being exceeded simultaneously at two sites is less than the probability of the same attenuation being exceeded at one of the sites by a factor that decreases with increasing distance between the sites and with increasing attenuation. Intense rain cells cause large attenuation values on an earth-space link and often have horizontal dimensions of not more than a few kilometers. SD systems can re-route traffic to alternate earth stations, resulting in considerable improvements in the system's reliability. A balanced SD system (with attenuation thresholds on the two links equal) uses a prediction method that computes the joint probability of exceeding attenuation thresholds, is considered the most accurate, and is preferred by ITU (ITU-R, 2009).

Power control (PC) is the process of varying the transmission of power on a satellite link in the presence of path attenuation to maintain a desired power level at the receiver. Power control attempts to restore the link by increasing the transmit power during a fade event and then reducing the power after the event is back to its non-fade value (Castanet *et al*., 2005).

Time Diversity (TD) can be considered a FMT that aims to re-send information when the state of the propagation channel allows it to be received. Oftentimes, it is unnecessary to receive the data file in real time, and it is acceptable from the user point of view to wait for the end of the propagation or for a reduction in traffic. This technique benefits from the use of a propagation mid-term prediction model to estimate the most appropriate time to re-send the message without repeating the request (Castanet *et al*., 2005).

Reconfigurable Antenna Pattern (RAP) is an emerging technology. It is envisaged to be implemented on the space end of the satellite communication link. It is intended to adaptively vary the-board antenna characteristics, such as the gain, when problems such as signal fading, depolarization, and co-channel polarization due to scattering are experienced along the satellite link. For instance, the antenna gain is expected to be increased momentarily during these events to compensate for the signal attenuation, and only for the preset gain to be restored when the events no longer subsist. One design is a 2x2 MIMO antenna configuration.

Rain Attenuation Models

There are as many as sixteen rain attenuation models in the literature (Harris, 2001). The International Telecommunication Union-Radio Communication Sector (ITU-R) model was judged as the most widely accepted internationally for the prediction of rain effects on communication systems. Hence, most emerging models are compared against it for conformity and reliability. Several specific models can satisfactorily address the challenges of terahertz (THz) frequency signal attenuation due to rain and other atmospheric conditions. These models are shown in Table 1:

Table 1: Some Specific Models that address Terahertz (THz) frequency Bands

Ref.	Model	Description of the Model
ITU-R. (2005).	**ITU-R P.838-3**	The International Telecommunication Union Radio communication Sector (ITU-R) Recommendation P.838-3 provides specific attenuation models for rain for frequencies up to 1000 GHz, which covers the THz range.
ITU-R. (2019).	**ITU-R P.676-12**	This recommendation deals with the attenuation by atmospheric gases. While it is primarily for frequencies up to 1 THz, it provides valuable information on how gases like oxygen and water vapour affect THz signal propagation.
(Bohren	**Mie Scattering**	This theoretical model calculates the scattering and

and Huffman, 1983)	**Theory**	absorption of electromagnetic waves by spherical particles, such as raindrops, and is crucial for understanding how raindrops of various sizes affect THz waves.
Strutt, J. W. (Lord Rayleigh). (1899).	**Rayleigh Scattering**	Applicable for very small raindrops compared to the wavelength, this model helps understand the scattering behaviour for different raindrop sizes and frequencies.
(Liebe, 1989).	**Liebe's Model (1989)**:	This model, developed by H.J. Liebe, describes the absorption of electromagnetic waves by water vapour and oxygen, particularly in the millimeter and THz wavebands.
Crane, R. K. (1980)	**Crane Global Model**	While primarily used for microwave frequencies, the Crane model can be extended to higher frequencies, including THz, to estimate rain attenuation.
(Rothman et al. 2013)	**Hitran Database**	The High-resolution Transmission Molecular Absorption Database (HITRAN) provides absorption coefficients for various atmospheric gases, which is critical for understanding THz signal attenuation due to atmospheric conditions.
(Van de Hulst, 1957).	**Van de Hulst's Approximation**	This is an approximation used for scattering and absorption calculations, particularly for non-spherical particles, and can be adapted for use in the THz range.
(Yamamoto & Imai 2002).	**Yamamoto and Imai Model**:	A model developed for the THz frequency range that considers both rain and molecular absorption for estimating signal attenuation
(Rice & Holmberg, 1973)	**Rice-Holmberg Model**:	This model provides attenuation estimates for rain and is often used in conjunction with empirical data to adjust for THz frequency effects.
(Peters et at, 2002).	**Empirical and Semi-Empirical Models**	These models are based on experimental data collected from measurements of THz wave propagation in different weather conditions, providing empirical formulas to predict rain attenuation accurately
(Zhao & Li, 2003).	**Zhao's Model (2003)**:	This model provides empirical data-based predictions for rain attenuation in the millimeter-wave band, which can be extrapolated to the lower end of the THz range.

Conclusion:

Terahertz-band communication holds immense potential for future wireless data transmission due to its ability to support ultra-high-speed links. However, rain-induced attenuation poses a significant challenge to its implementation. This paper reviews various mitigation techniques and models that address this issue. Amplification, equalization, forward error correction, and diversity techniques provide robust solutions to maintain signal integrity. Additionally, adaptive coding and modulation, site diversity, and power control offer dynamic responses to varying rain conditions, ensuring consistent quality of service (QoS). Empirical models like ITU-R and theoretical models such as Mie Scattering and Liebe's provide accurate predictions for rain attenuation, aiding in the design of effective mitigation strategies. Implementing these techniques can significantly enhance the reliability and performance of THz-band communication systems, paving the way for their widespread adoption in future wireless networks.

Abbreviations:

Terabit-per-Second	(Tbps)
Quality of Service	(QoS)
Adaptive Coding and Modulation	(ACM)
Reconfigurable Antenna Pattern	(RAP)
Time Diversity	(TD)
Site Diversity	(SD)
Power Control	(PC)
Signal-to-Noise Ratio	(SNR)
Maximal-Ratio Combining	(MRC)
Fade Mitigation Technique	(FMT)

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Atser and Omolaye, write the original draft preparation, and conceptualization, Mom and Atsuwe proof read the work. Gesa review the language and presentation of the work.

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