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RESEARCH ARTICLE

Adaptive Bandwidth Allocation for Sub-THz and Terahertz Wireless Links

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ABSTRACT: Future 6G wireless systems are expected to exploit sub-terahertz (sub-THz) and terahertz (THz) frequency bands to enable extremely high data rates. However, these bands suffer from severe propagation losses due to free-space path loss, molecular absorption, blockage, and hardware limitations. This project proposes adaptive bandwidth allocation as a practical mechanism to improve link reliability by concentrating transmit power over a reduced bandwidth when channel conditions degrade. The study, analysis, and conclusion are based on simulation and theoretical data.

KEYWORDS: Wireless Communications, Terahertz Communication, 6G, Adaptive Bandwidth, Uplink Limitation.

Introduction

THz communication offers a large bandwidth but experiences extreme attenuation, limiting coverage and reliability, particularly in uplink-limited scenarios.[1] This study independently models the impact of adaptive bandwidth allocation on uplink-limited sub-THz links using MATLAB simulations. Unlike prior survey-based work, this paper quantitatively demonstrates how bandwidth reduction improves per-resource-element power, SINR, and BLER under realistic UE power constraints. This study primarily focuses on uplink-limited performance in sub-THz and THz systems under strict UE transmit power constraints, while downlink is discussed as a secondary consideration. Unlike prior adaptive sub-band allocation studies that primarily address spectrum efficiency or throughput optimization, this work is explicitly for per-resource-element power concentration under fixed UE transmit power.

Results and Discussion

Background and related work:

Propagation at terahertz frequencies is dominated by free-space path loss, which increases quadratically with carrier frequency.[2] Even over short distances, this results in significant signal attenuation.

In addition, molecular absorption by atmospheric gases such as water vapor and oxygen introduces frequency-selective attenuation,[3] creating usable transmission windows separated by absorption peaks. Environmental factors such as humidity, rain, and fog further exacerbate signal degradation.

Due to the extremely short wavelengths, THz signals exhibit poor diffraction around obstacles and experience severe penetration loss through common materials. As a result, reliable non-line-of-sight communication is extremely challenging.

In cellular systems, uplink communication is inherently constrained by user equipment (UE) transmitting power limitations. At THz frequencies, the use of extremely wide bandwidths significantly increases the receiver noise floor, further degrading uplink performance.[4]

Unlike base stations, UE devices are limited in antenna size, beamforming capability, and thermal dissipation. These constraints make uplink coverage one of the most critical bottlenecks in THz-based cellular architecture.

The following plots provide insight into expected terabit-per-second data rates and the available frequency bands within the terahertz spectrum.

The evolution of peak data rates for cellular and Wi-Fi technologies is shown in Figure 1, while the electromagnetic spectrum and the terahertz frequency bands are illustrated in Figures 2 and 3, respectively.

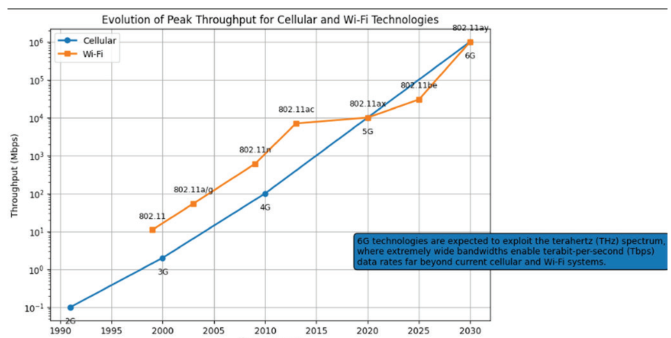

Figure 1: Evolution of peak data rates for cellular and Wi-Fi technologies. The figure highlights the exponential growth in peak data rates over successive generations, motivating the need for sub-THz and THz spectrum utilization in future 6G systems.

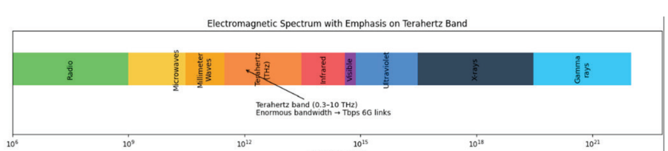

Figure 2: Electromagnetic spectrum. This figure situates the terahertz band between microwave and infrared frequencies, illustrating its potential for ultra-wide bandwidth communications.

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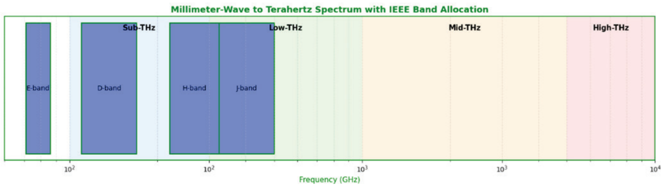

Figure 3: The terahertz spectrum shows different frequency bands. The figure emphasizes available transmission windows separated by molecular absorption peaks, which are critical for adaptive bandwidth allocation.

The dominant attenuation mechanisms affecting terahertz links are depicted in Figure 4, and the simulated RSRP variation across terahertz frequencies is shown in Figure 5.

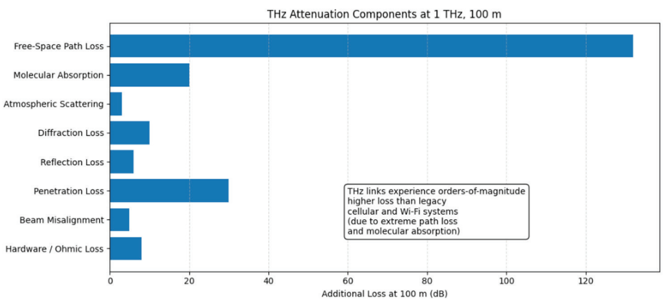

Figure 4: Different attenuation mechanisms in terahertz communication systems. The figure highlights the dominant contributions of free-space path loss, molecular absorption, and blockage to overall link attenuation.

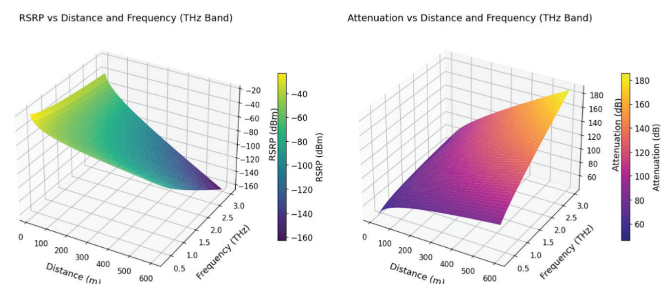

Figure 5: MATLAB simulation showing the device received RSRP and attenuation for different terahertz frequencies. The results demonstrate the rapid degradation of received power as frequency increases, underscoring uplink limitations at higher bands.

Current mitigation techniques

• Ultra-massive MIMO and beamforming: Very large antenna arrays are used to create highly directional, high-gain beams that compensate for the severe free-space path loss experienced at terahertz frequencies.

• Intelligent reflecting surfaces (IRS/RIS): Reconfigurable passive surfaces are deployed to establish virtual line-of-sight paths, mitigating blockage and non-line-of-sight propagation losses.

• Ultra-wide and adaptive bandwidth: Large terahertz bandwidths and frequency-dependent absorption windows are dynamically exploited to sustain high data rates under strong attenuation.

• Ultra-dense small-cell deployment: Communication distances are reduced to tens of meters, significantly lowering propagation loss and improving link reliability.

• Relay-assisted and multi-hop transmission: Long terahertz links are divided into multiple shorter hops, reducing cumulative path loss and improving coverage.

• Hybrid sub-terahertz, terahertz, and millimeter-wave operation: Lower-frequency bands are used for control signaling and fallback connectivity, while terahertz bands support ultra-high-data-rate transmissions.

• Joint communication and sensing (JCAS): Integrated sensing enables environment-aware beam tracking and blockage prediction, reducing beam misalignment losses.

• Advanced terahertz hardware and materials: Low-loss devices, antennas, and RF front-end components minimize ohmic and hardware-induced losses.

• Advanced coding and waveform design: Terahertz-optimized modulation and channel coding schemes enhance robustness under low signal-to-noise ratio conditions.

Proposed methodology:

Dynamic bandwidth adaptation adjusts the active bandwidth based on channel quality metrics to improve per-subcarrier SNR and robustness. Bandwidth adaptation is controlled by simple thresholds based on uplink SINR, downlink RSRP, and UE power headroom. When the SINR drops below a set threshold or when the UE is close to its maximum transmit power, the system reduces the allocated bandwidth step by step. When SINR and RSRP improve and remain stable, the system returns to full bandwidth operation. The current manuscript does not consider mobility and Doppler effects. Future extensions will incorporate mobility models and Doppler effects to evaluate bandwidth adaptation under dynamic conditions.

The core idea exploits the intrinsic bandwidth abundance of THz systems and the scarcity of transmitting power at the UE. When downlink reference signal received power (RSRP), uplink or downlink SINR, and UE power headroom indicate favorable channel conditions, the system utilizes a wide or full bandwidth to maximize throughput. As channel conditions deteriorate due to increased distance, absorption, blockage, or mobility, the active OFDMA/SC-FDMA grid is progressively scaled down. By reducing the number of active subcarriers, the available transmit power is concentrated over a narrower bandwidth, resulting in higher per-subcarrier power, improved uplink SINR, reduced block error rate, and extended coverage.

Simulation results:

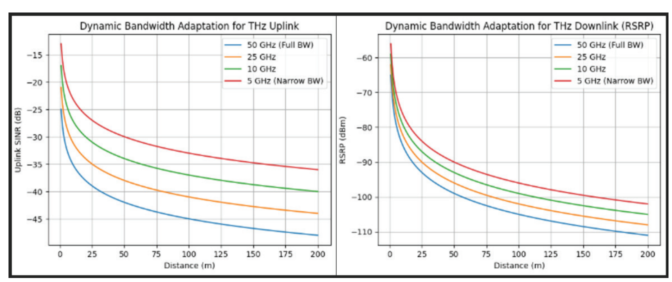

Figure 6: MATLAB simulation showing the device received RSRP and SINR with distance due to attenuation. The figure shows that both RSRP and SINR decrease sharply with distance, motivating adaptive bandwidth strategies for maintaining link reliability.

Figure 6 illustrates the relationship between allocated bandwidth and transmit power per resource element (RE) for a low sub-THz OFDM system with fixed total transmit power. The plot demonstrates that, as the allocated bandwidth is reduced, the number of active subcarriers and REs decreases, resulting in a higher transmit power per RE. In particular, halving the bandwidth leads to an approximately 3 dB increase in per-RE power, consistent with energy concentration over fewer transmission resources. This behavior is especially relevant for sub-THz links, where propagation loss and blockage can significantly degrade link quality. When channel conditions are favorable, the system operates with full bandwidth to maximize throughput. However, as link quality deteriorates due to reduced SINR or RSRP, dynamic bandwidth reduction can be employed to increase per-RE power and improve link robustness. The figure highlights bandwidth adaptation as an effective mechanism for maintaining reliable communication in challenging sub-THz propagation environments without increasing total transmit power.

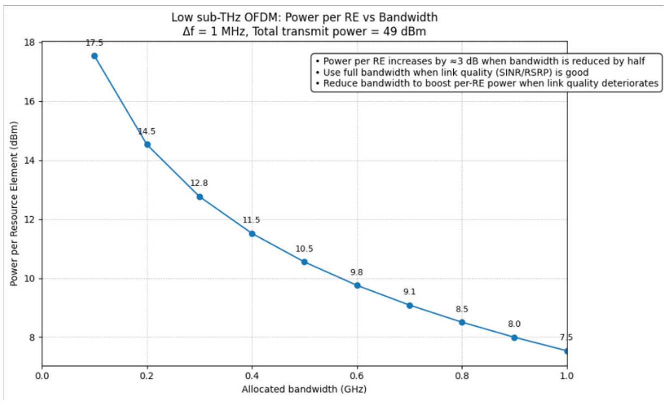

Figure 7: Transmit power per resource element (RE) versus allocated bandwidth for a fixed total transmit power. Reducing bandwidth concentrates power over fewer REs, resulting in an approximately 3 dB increase in per-RE power when bandwidth is halved.

Reducing the allocated bandwidth by half increases the transmit power per resource element by approximately 3 dB. Full bandwidth operation is preferred when link quality indicators such as SINR and RSRP are high, while bandwidth reduction improves robustness under degraded channel conditions.

In the current study, bandwidth reduction is modeled as uniform scaling of the allocated spectrum rather than selecting specific sub-bands. The system reduces the overall bandwidth evenly instead of choosing lower-loss frequency segments. Investigating selective sub-band allocation could be explored in future work.

The plots (Figure 7) illustrate the impact of bandwidth adaptation on link performance by showing the relationship between allocated bandwidth and key metrics, including RSRP, SINR, UE transmit power, and downlink BLER. As the bandwidth is reduced, transmitting energy is concentrated over fewer resource elements, resulting in increased per-RE power. This leads to improved RSRP and SINR, which in turn reduces downlink BLER and lowers the required UE transmit power. When link quality is good, full bandwidth operation maximizes throughput, while bandwidth reduction under degraded channel conditions enhances link robustness without increasing total transmit power.

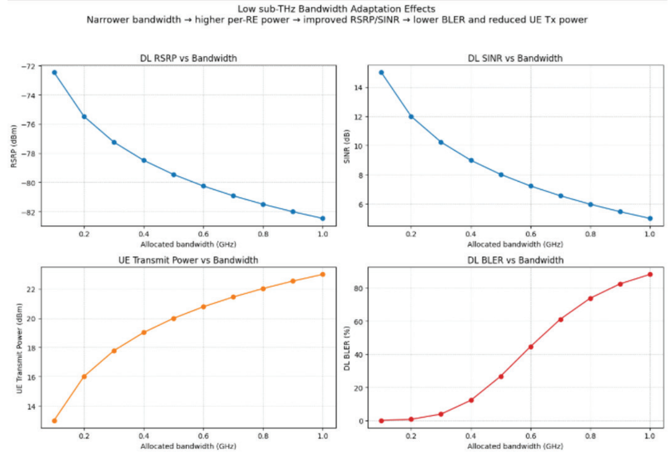

Figure 8: Impact of adaptive bandwidth allocation on link performance. Bandwidth reduction increases per-RE power, improving RSRP and SINR while reducing BLER and required UE transmit power under degraded channel conditions. The figure confirms that adaptive bandwidth improves robustness without increasing total transmit power.

Effect of uplink RSSI on allocated bandwidth:

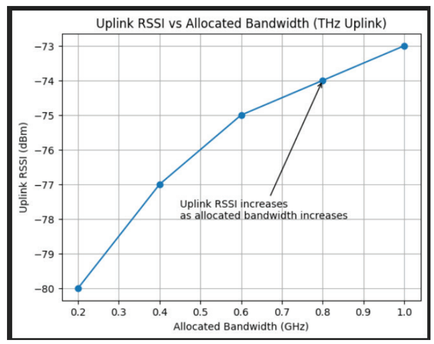

Figure 9: Uplink RSSI versus allocated bandwidth. The figure shows that uplink RSSI increases with bandwidth due to the accumulation of received signal power across a wider spectrum.

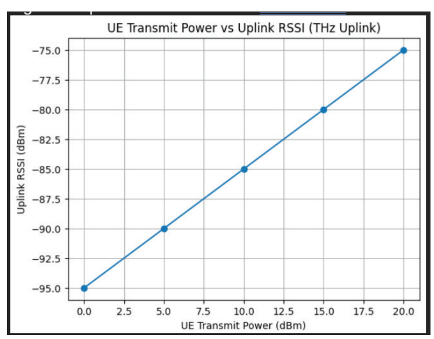

Figure 10: Uplink RSSI versus UE transmit power. The figure highlights the strong dependence of UE transmit power on RSSI, demonstrating the power constraints that limit uplink performance at terahertz frequencies.

Figures 7–10 represent simulation results that are applicable to both sub-THz and THz communication systems, illustrating general trends in bandwidth adaptation and power concentration under uplink power constraints.

As the allocated bandwidth increases, the uplink RSSI increases mainly for two reasons. First, uplink RSSI represents the total received signal power across the entire bandwidth.

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When a wider bandwidth is used, the receiver collects signal energy from a larger portion of the spectrum. As a result, more signal power is accumulated at the receiver, leading to a higher measured uplink RSSI.

Second, in the Terahertz frequency range, signal attenuation is not uniform across all frequencies. Some parts of the spectrum experience higher loss due to molecular absorption, while others have relatively lower attenuation. By allocating a wider bandwidth, the uplink signal is more likely to include these lower-loss frequency regions, which contribute more effectively to the received signal power and further increase the uplink RSSI.

As uplink RSSI increases, the UE transmit power also increases to support reliable uplink communication. Wider bandwidth operation raises the noise level and increases system sensitivity requirements. To maintain a strong and detectable uplink signal at the base station, the UE must transmit more power. This relationship highlights a key challenge in Terahertz systems, where UE power constraints strongly limit uplink performance.

The improvement of performance is most noticeable in uplink power-limited scenarios, where the user device has limited transmit power when using very wide bandwidths. When the bandwidth is reduced, the transmit power is concentrated over fewer resource elements, which improves uplink SINR and link reliability. In downlink-dominated scenarios, a similar effect may occur, but the improvement is expected to be smaller because base stations usually have higher transmitted power and stronger beamforming capability.

Bandwidth reduction primarily affects throughput rather than intrinsic propagation delay. In fact, by preventing retransmissions and reducing block error rate under poor channel conditions, adaptive bandwidth may indirectly improve effective latency. However, since lower bandwidth reduces peak data rate, large payload transmissions may experience slightly increased transmission time.

Adaptive bandwidth mechanisms are particularly relevant for 6G use cases such as extended reality (XR), remote healthcare procedures, and autonomous vehicles. These applications require both high data rates and reliable connectivity. During favorable conditions, wide bandwidth supports immersive XR or high-resolution medical imaging, while under degraded conditions, bandwidth reduction can maintain a stable link for control signaling and safety-critical communication.

Conclusion

Adaptive bandwidth allocation provides a low-complexity and effective solution for uplink-limited sub-THz and THz systems4 by dynamically adjusting bandwidth to balance link quality and data rate. It can also support downlink performance when signal strength or SINR degrades, enabling an optimal trade-off between throughput and reliable communication. The proposed approach prioritizes maintaining a stable connection under degraded conditions, sacrificing peak data rate temporarily to prevent link failure. Simulation results show that reducing bandwidth improves per-resource-element power and reduces BLER in uplink-limited sub-THz links.

Limitations

This study is based on theoretical modeling and MATLAB simulations and does not include hardware measurements. At present, experimental validation in a home or small field setup is not feasible. However, future work will aim to validate the proposed approach using laboratory-grade sub-THz testbeds once appropriate research lab access and high-frequency measurement infrastructure become available.

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