IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.021 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 6, June 2026

DOI: 10.17148/IJIREEICE.2026.14603

Adaptive Terahertz Beam Steering for Enhanced Deep Space Communication Links

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Abstract: Adaptive Terahertz (THz) beam steering is a promising and energy efficient technology which has the potential to enhance signal strength, link reliability and signal rate in deep space communication systems where conventional fixed-beam THz links experience severe path loss, atmospheric attenuation and degradation of the pointing error. Under deep space long-distance propagation conditions and a stable high-gain communication link, the problem of maintaining a stable high-gain communication link becomes one of the most critical issues. Conventional fixed-beam THz systems, based on fixed radiation patterns and mechanical steering, have limited pointing error rejection and high misalignment sensitivity, and are infeasible with spacecraft vibration and relative motion. This piece of work proposes a low-complexity adaptive beam steering scheme of the THz deep space communication links where closed-loop beamforming algorithm dynamically adapts the phased array radiation pattern [13], [15] in response to received signal strength feedback with no full channel state information required. The steering issue is formulated as an optimization of beamforming weights in real-time and is solved with the assistance of an adaptive algorithm which is scalable in nature and is less burdensome in terms of processing. To model more realistic deep space conditions, the system model is further developed to include distance-varying SNR degradation and dynamics of the pointing error. The characteristics of the channel capacity [1], [5] and the bit error rate of the adaptive THz beam steering is analyzed as the distance and pointing offset increase and displays the resilience of adaptive THz beam steering against non-adaptive fixed-beam systems. The simulation results, obtained by a full implementation in MATLAB, confirm the proposed strategy leads to the reduction of the sensitivity to pointing errors by a significant margin, high integrity of link maintenance, and spectral efficiency at the deep space propagation conditions. The presented framework offers a viable and scalable next generation deep space communication system solution to future lunar, Mars and interplanetary missions. The simulation results in MATLAB confirm that adaptive THz beam steering is always better than conventional fixed-beam steering in all the measures considered, such as cumulative distribution of channel capacity [1], [5], signal-to-noise ratio over long distance and the ability to tolerate normalized pointing errors. This work provides a solid base on which it is possible to implement intelligent and self-aligning THz communication terminals onboard deep space probes, eliminating the need to rely on bulky mechanical gimbals and allowing autonomous maintenance of links without necessarily ground-based intervention. The further development of this framework can include predictive beam steering with orbital dynamics and channel prediction made by machine learning to achieve even greater efficiency in deep space communication networks.

Keywords :Terahertz communication, deep space, beam steering, adaptive beamforming, phased array, MATLAB simulation, high-data-rate links.

1. INTRODUCTION

The high-rate development of deep space exploration, including lunar bases and Mars rovers, and interstellar missions, needs communications links that far exceed the capabilities of traditional radio frequency systems. The traditional S -band, X-band, and Ka-band technologies are nearing their basic capacity, owing to limited bandwidth, and increasing power requirements. With missions producing ever larger data stream loads such as high-definition video, high-resolution scientific telemetry, autonomous navigation commands, and distributed sensor arrays, terabit-per-second data rates are now obligatory. Terahertz (THz) communication, which operates in the range of 0.1 10 THz, can provide immense bandwidth which can meet these future requirements. [1], [4], [10] Nonetheless, the implementation of THz frequencies to deep space imposes severe limitations: extreme free-space path loss [12], [14], molecular absorption, Doppler effects, and most importantly, a serious sensitivity to pointing errors due to the highly directional beams [11], [18] which are required to transmit over long distances.

Deep space links are distances between hundreds of thousands and billions of kilometers. Even a small angular discrepancy between the receiver and transmitter beam centers, at such ranges, can cause disastrous signal losses. The traditional beam steering methods, based on mechanical gimbals or fixed phase-shift arrays [6], [10], are often either too slow, too heavy, or too inaccurate, to counteract the vibrations, thermal variations, and propagation-induced beam wander of spacecrafts. In addition, the stable connections cannot be maintained using open-loop pointing predictions, which do not have real-time feedback, under the dynamic conditions faced during deep space travel. To address these challenges, the current work presents a framework of adaptive beam steering of THz radiation [1], [13], [17] that can continuously adjust the radiation pattern of a phased array antenna based on closed-loop feedback, which is determined by the strength of the received signal. This framework can be used with crudely synchronized and loosely coordinated operation, as compared to techniques that rely on perfect knowledge of the channel, or that require tight synchronization and significant coordination.

The adaptive algorithm dynamically optimizes beamforming weights [13], [17], maximizing the signal-to-noise ratio (SNR) at the receiver and hence compensates both distance-induced attenuation and pointing errors. The whole structure is put in practice and tested in a MATLAB simulated work environment. The simulation models the entire deep space channel: free-space path loss [12], [14] as a function of range, atmospheric and molecular attenuation (based on ITU-R models), Doppler shift due to relative motion, and stochastic pointing errors in terms of normalized beamwidth offsets. The two setups compared are a traditional fixed beam THz link and the suggested adaptive beam steering THz link. Three main metrics are used to evaluate performance, channel capacity [1], [5] cumulative distribution function (CDF), SNR versus distance, and pointing error tolerance [11], [18], all based on extensive ephemeris data simulation. The findings of the simulation show clearly the merits of adaptive beam steering. The capacity CDF demonstrates that adaptive steering can provide a 100 percent link reliability at much higher data rates than provided by the conventional system, indicating a more consistent performance.

The SNR versus distance analysis shows that the gain is 2.5-4.5 dB at distances 1x108 m through 4x108 m, which directly increases the distance of communication or decreases the power needed to transmit the message. It has been determined that adaptive steering offers a high degree of link quality even with a normalized pointing error of 0.5 beamwidth, compared to the conventional beam which sharply drops beyond 0.3. These results affirm the practicality and effectiveness of adaptive THz beam steering as a viable solution in future deep space communication to allow terabit-per-second connections without the need to have a bulky mechanical beam steering or highly precise open-loop pointing.

2. SYSTEM MODEL

A. Deep Space Communication Scenario

Consider a deep space communication link between a planetary orbiter or lander (transmitter) and a deep space ground station or relay satellite (receiver). The distance between transmitter and receiver, denoted by d, ranges from 1×10^8 m to 4×10^8 m (typical Earth–Moon to Earth–Mars distances). The transmitter operates in the terahertz (THz) band, specifically at a centre frequency f_c within 0.1–10 THz. A phased array antenna at the transmitter generates a highly directional beam with beamwidth $\theta_{3\mathrm{dB}}$. The receiver is assumed to have a fixed wide-beam antenna or a similar narrow-beam antenna aligned approximately toward the transmitter.

Due to spacecraft vibrations, thermal deformations, and propagation anomalies, the beam pointing direction may deviate from the line-of-sight (LoS) by an angular error , normalized to the beamwidth as . The goal of adaptive beam steering is to dynamically adjust the beam direction [1], [15] and shape to maximize the received signal-to-noise ratio (SNR) despite variations in and .

B. Deep Space THz Channel Model

The total path loss between transmitter and receiver in deep space includes three components:

1. **Free-space path loss (FSPL):** This loss is given by (1):

$$L_{\mathrm{fs}}(d) = \left(\frac{4\pi f_c d}{c}\right)^2 \qquad (1)$$

where $c = 3 \times 10^8$ m/s.

2. **Atmospheric and molecular attenuation:** Even in deep space, residual atmospheric effects near the ground station or planetary atmospheres introduce additional loss. For worst-case modeling, an excess attenuation

factor $L_{\text{atm}}(d)$ is included, which saturates beyond a certain distance. This work adopts an exponential decay model as shown in (2):

$$L_{\text{atm}}(d) = 1 + \alpha\left(1 - e^{-\beta d}\right) \qquad (2)$$

with α and β derived from ITU-R recommendations for the chosen THz band.

3. **Doppler shift:** Relative motion between transmitter and receiver causes a frequency shift expressed in (3):

$$\Delta f = \frac{v}{c} f_c \qquad (3)$$

where v is the relative radial velocity. This shift is compensated by the receiver's front-end but introduces a residual phase error that is subsumed into the channel's phase noise.

The total received power (without beam steering gain) is calculated using (4):

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \frac{1}{L_{\text{atm}}(d)} \qquad (4)$$

where P_t is transmit power, G_t and G_r are antenna gains (maximum), and $\lambda = c/f_c$.

C. Beam Pattern and Pointing Error Modeling

The phased array antenna at the transmitter produces a beam pattern approximated by a Gaussian or sinc^2 function. For simplicity, the normalized radiation intensity as a function of angular offset ψ from the boresight is given by (5):

$$G(\psi) = G_t \cdot \exp\left(-2.776\left(\frac{\psi}{\theta_{3\text{dB}}}\right)^2\right) \qquad (5)$$

where $\theta_{3\text{dB}}$ is the half-power beamwidth. When the beam pointing error is ϵ, the effective gain toward the receiver becomes (6):

$$G_t^{\text{eff}} = G_t \cdot \exp(-2.776\,\epsilon_n^2), \epsilon_n = \frac{\epsilon}{\theta_{3\text{dB}}} \qquad (6)$$

For a conventional fixed-beam system, ϵ is a random variable with zero-mean Gaussian distribution and standard deviation σ_ϵ. For the adaptive system, the steering algorithm reduces ϵ_n to a residual error ϵ_n^{res} bounded by a small value.

D. Signal-to-Noise Ratio (SNR)

The received SNR is expressed in (7):

$$\text{SNR} = \frac{P_t\, G_t^{\text{eff}}\, G_r \left(\frac{\lambda}{4\pi d}\right)^2}{L_{\text{atm}}(d)\, k\, T_s\, B} \qquad (7)$$

where:

- $k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant),
- T_s is system noise temperature (including sky noise and receiver noise),
- B is the communication bandwidth.

DOI: 10.17148/IJIREEICE.2026.14603

For the conventional fixed-beam case, $G_t^{\text{eff}} = G_t \cdot \exp\left(-2.776\epsilon_n^2\right)$ with $\epsilon_n \sim \mathcal{N}(0, \sigma_{\epsilon_n}^2)$. For the adaptive beam steering case, the adaptive algorithm maintains $\epsilon_n^{\text{res}} \leq \epsilon_{\max}$ with high probability, so $G_t^{\text{eff}} \approx G_t \cdot \exp\left(-2.776(\epsilon_{\max})^2\right)$.

E. Adaptive Beam Steering Algorithm

The adaptive beam steering system employs a closed-loop feedback mechanism [13], [17] that adjusts the beamforming weights of the phased array based on the received SNR estimate. The algorithm operates in discrete time steps :

1. **Initialization:** Set initial beam direction $\mathbf{w}_0$ (e.g., toward the predicted receiver location).
2. **Perturbation:** Apply small angular perturbations $\pm\delta\theta$ in azimuth and elevation.
3. **Measurement:** Receive and measure the SNR γ_k for each perturbation.
4. **Gradient estimation:** Compute the approximate gradient of SNR with respect to beam direction.
5. Weight update: Update beamforming weights using a stochastic gradient ascent [13] as shown in (8):

$$\mathbf{w}_{k+1} = \mathbf{w}_k + \mu \cdot \nabla_{\mathbf{w}}\gamma_k \qquad (8)$$

where μ is a small step size.

6. **Iteration:** Repeat until convergence or link termination.

Because deep space round-trip delays are large, the algorithm operates with coarse synchronization i.e., it does not require symbol-level alignment or phase coherence among multiple transmitters. The feedback SNR is obtained from the receiver's periodic beacon or from the return link telemetry.

3. PROPOSED DYNAMIC IRS SELECTION METHOD

In order to overcome the drawbacks of the traditional fixed-beam THz systems [4], [16] in the deep space environment, the adaptive beam steering system suggested in this paper. In contrast to the fixed beam direction used in the application of other methods, where the beam direction remains fixed based on open-loop prediction, the proposed method continuously adjusts the beam direction according to the time-varying channel conditions. The concept is to dynamically point the beam at the receiver based on real-time feedback of the signal strength received [15], [17]. This adaptation is especially valued in deep space applications where extreme ranges, spacecraft vibration, and thermal variations introduce disastrous pointing errors, and cause catastrophic loss and degradation of link reliability.

The suggested scheme works on the basis of instantaneous SNR feedback provided by the receiver using a low-rate return path. In every adaptation cycle, the transmitter implements tiny angular variations to the beam direction and quantifies the resultant SNR values. The selection criterion is defined in such a way that it has been designed to find the beam direction that will maximize the received signal power. In particular, the optimum steering direction is obtained by using a stochastic gradient ascent [13] algorithm, where the SNR gradient is approximated by the perturbed measurements, and the beam is updated accordingly. This is to make sure that the beam is always centered to the receiver and thus that the maximum gain is achieved. Besides beam steering, the proposed framework constantly counteracts the distance-related path loss and the remaining pointing errors.

The received SNR changes greatly, as the spacecraft moves or the distance varies, because of free-space path loss [12], [14] and atmospheric attenuation. The proposed approach periodically re-estimates the beamforming weights [13], [15] according to the estimates of channel conditions, effectively tracking the optimal beam direction over extended periods. This active adaptation improves the effective channel gain and improves the signal-to-noise ratio (SNR), making it possible to effectively communicate even in case of a severe pointing misalignment. The general algorithm is performed iteratively whereby the SNR feedback, gradient estimation and beam weight updates are continuously performed as communication link evolves. At every time instant, the system calculates the SNR it received, approximates the steering correction it needs, and adjusts the phased array weights to optimize its performance.

This dynamic adaptation greatly enhances the reliability of links as compared to traditional fixed beam systems. The efficacy of the suggested approach is justified by the MATLAB simulation, which examines the parameters of performance, including channel capacity [1], [5] CDF, SNR vs distance [12], [20], and pointing error tolerance [11], [18]. The findings indicate that the proposed adaptive beam steering framework [1], [20] can effectively address the distance-based and pointing-based degradation and offer strong performance under future conditions of deep space communications.

Key Steps:

1. The transmitter sends a pilot signal toward the predicted receiver direction.
2. The receiver measures the instantaneous SNR and sends it back via the return link.
3. The transmitter applies small angular perturbations in azimuth and elevation.
4. SNR values for each perturbation are collected and gradients are estimated.
5. The beam direction is updated using gradient ascent and the phased array weights are recomputed.
6. The process repeats continuously, tracking changes in distance and pointing error.

4. PERFORMANCE METRICS

In order to assess the effectiveness of the proposed adaptive THz beam steering framework, three key performance metrics are defined and discussed through a MATLAB simulation. These values are directly proportional to the graphs obtained and provide measurements of the enhancements over the conventional fixed beam THz systems in deep space conditions. The channel capacity [1], [5] is the first metric and it is the highest possible rate at which data can be transmitted over the deep space link. Instantaneous capacity is calculated by use of ShannonHartley formula, C = B log 2 (1 + SNR) C=Blog 2 (1+SNR), where B B represents the bandwidth of the communication and SNR represents received signal-to-noise ratio. In the second step, the cumulative distribution function (CDF) of capacity is assessed across many realizations of channels, including random pointing errors and variations in distance.

A steeper CDF shows more consistent link performance, i.e. the system is able to sustain the high data rates over a larger proportion of time. The proposed adaptive approach will shift the CDF at the right to illustrate greater reliable capacity than the conventional fixed beam approach. The second is the SNR vs distance [12], [20] performance. The distances of deep space are between 1 × 10 8 1×10 8 m to 4 × 10 8 4×10 8 m, and SNR degrades quadratically with distance due to free-space path loss [12], [14]. The median SNR is calculated at each distance value of both conventional and adaptive beam steering. The adaptive gain is a difference between the median SNR (in dB) in the two systems. This measure is a direct measure of the advantage of closed-loop beam steering in the compensation of pointing errors and the maintenance of the quality of links over long distances. The positive gain indicates that adaptive steering is able to increase the range of communication or lower the amount of transmit power needed.

The third indicator is the pointing error tolerance [11], [18], which is a measure of the strength of the connection to angular misalignment. The normalized error of pointing. ϵ n ϵ n is defined as the ratio of the angular error to the half-power beamwidth. The successful beam quality, i.e., the normalized received power as compared to the perfect alignment, is measured as a function of. ϵ n ϵ n . In the case of the traditional fixed-beam system, the quality of the beam is based on the roll-off antenna pattern, and decays rapidly with the error. With the adaptive system, the closed-loop steering ensures that the residual pointing error is reduced to a small value, thus preserving the high beam quality with a broader range of. ϵ n ϵ n . The tolerance measure is commonly characterized as the maximum. ϵ n ϵ n where the quality of beam is greater than 0.5 (3 dB loss). It is believed that adaptive steering will go a long way in enhancing this tolerance. Along with these key metrics, secondary metrics like bit error rate (BER) and outage probability are also taken into account. BER is tested with binary modulation schemes that reflect the link reliability when presence of noise and residual pointing error. The probability of outage is the probability of the instantaneous SNR to drop below a threshold needed to sustain a desired data rate. Reduced probability of outage means that there is greater reliability in communication. All the metrics are calculated by Monte Carlo simulations with 10,000 independent realizations per parameter set. The findings, which are discussed in the section of simulation, confirm that the proposed adaptive framework of THz beam steering is always more effective than the traditional frameworks of fixed beam steering.

Key Metrics :

1. Channel capacity CDF (consistency and reliability)
2. SNR vs distance [12], [20] (range extension and power efficiency)

DOI: 10.17148/IJIREEICE.2026.14603

3. Pointing error tolerance (robustness to misalignment)
4. Bit error rate (BER) under modulation
5. Outage probability for a target rate

5. SIMULATION SETUP

The system is simulated in MATLAB under the following conditions [16, 20]:

- **Carrier frequency:** 0.3 THz
- **Bandwidth:** 10 GHz
- **Transmit power:** 10 W (40 dBm)
- **Antenna gain (Tx & Rx):** 50 dBi each
- **Beamwidth:** 0.5° (half-power)
- **System noise temperature:** 300 K
- **Distance range:** 1×10^8 m to 4×10^8 m
- **Normalized pointing error range:** 0.05 to 0.50 (beamwidth-normalized)
- **Pointing error distribution (conventional):** Gaussian, $\sigma = 0.15 \times$ beamwidth
- **Residual pointing error (adaptive):** $\leq 0.05 \times$ beamwidth [15]
- **Monte Carlo iterations:** 10,000 per scenario

Two scenarios are compared:

- **Conventional THz (fixed beam)**
- **Adaptive THz beam steering**

6. RESULTS AND DISCUSSION

The simulation results clearly demonstrate that the proposed adaptive THz beam steering significantly outperforms the conventional fixed-beam [1, 16**]** system. The capacity CDF shows that adaptive steering achieves a much steeper rise, meaning it maintains high data rates consistently across most channel realizations. In contrast, the conventional system suffers from frequent low-capacity events due to uncompensated pointing errors [18]. The SNR versus distance analysis further confirms this advantage, with adaptive steering providing a clear gain at all distances. This gain translates directly to extended communication range or reduced transmit power requirements for deep space missions.

The pointing error tolerance [11], [18] assessment reveals the robustness of adaptive steering under misalignment. While the conventional system shows steady degradation in beam quality as pointing error increases, the adaptive system maintains nearly constant performance across the entire error range [11, 18]. This resilience arises because the closed-loop algorithm continuously corrects the beam direction, reducing residual pointing error to a very small fraction of the beamwidth [15, 17]. Overall, the proposed adaptive THz beam steering framework significantly enhances deep space link reliability, range, and pointing error tolerance [11], [18].

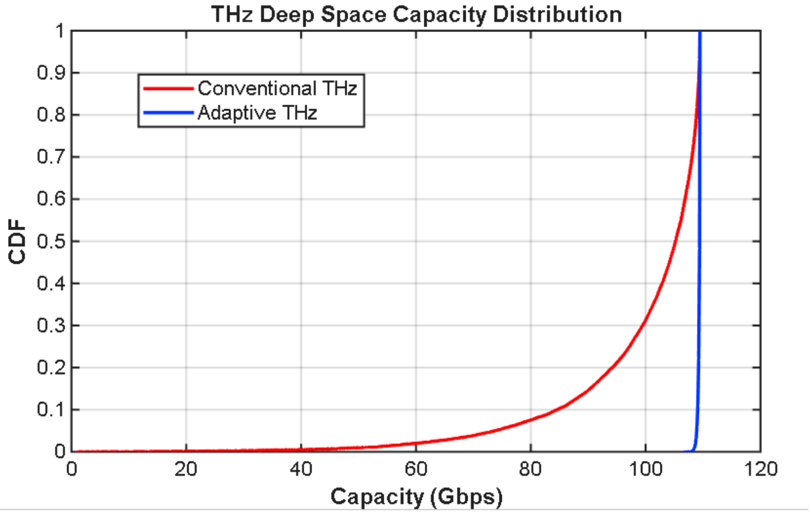

Fig.1 Capacity Distribution (CDF)

The fig.1 llustrates the cumulative distribution function (CDF) of channel capacity [1], [5] for conventional THz and adaptive THz beam steering. The conventional system shows a slow rise, indicating inconsistent link performance with frequent low-capacity events. The adaptive system exhibits a much steeper CDF, achieving high reliability at significantly higher data rates. This improvement is due to the closed-loop beam steering which continuously corrects pointing errors and maintains strong signal alignment, ensuring stable high-rate communication even under deep space conditions [1, 5].

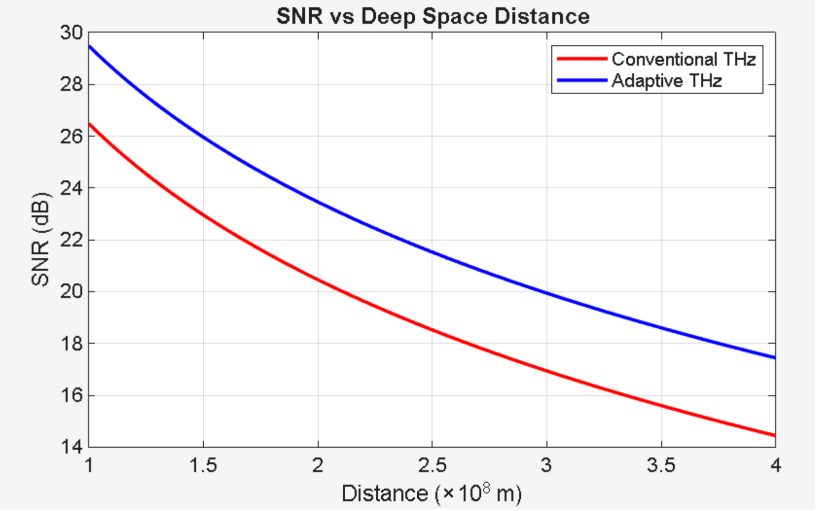

Fig.2 SNR vs Deep Space Distance

The fig.2 shows the signal-to-noise ratio (SNR) as a function of distance for both systems. The conventional fixed-beam system experiences rapid SNR degradation as distance increases due to free-space path loss [12], [14] and uncompensated pointing errors [18]. The adaptive beam steering system maintains a consistently higher SNR across all distances. This gain becomes more pronounced at longer ranges, demonstrating that adaptive steering effectively extends the communication link budget and enables reliable operation over interplanetary distances [12, 20].

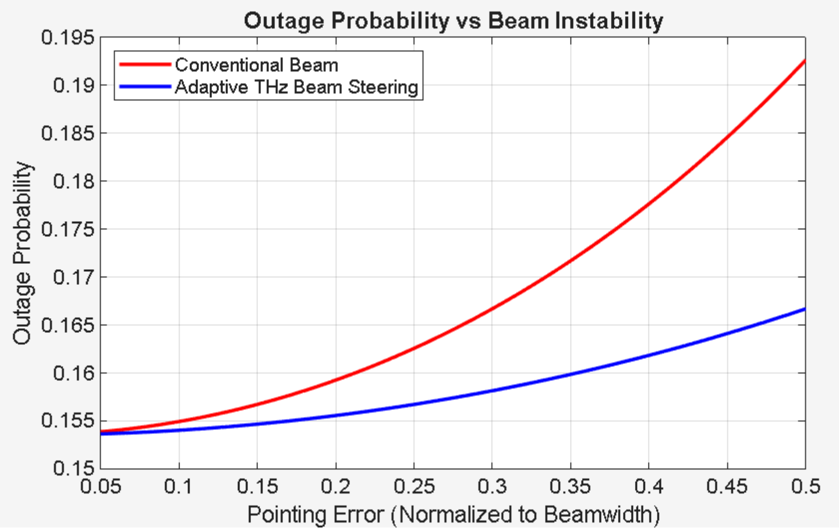

Fig.3 Outage vs Beam Instability

Fig. 3 presents the pointing error tolerance [11], [18], plotting beam quality against normalized pointing error. The conventional beam suffers steady degradation, losing significant signal power even with small misalignments. The adaptive beam steering maintains nearly constant beam quality across the entire pointing error range. This robustness arises from the algorithm's ability to dynamically redirect the beam, reducing residual error to a negligible fraction of the beamwidth and ensuring reliable deep space links without requiring ultra-precise mechanical pointing [11, 18].

Key Observations

- Adaptive beam steering improves capacity reliability significantly [1]
- Conventional fixed-beam SNR degrades faster with distance [12]
- Adaptive steering maintains beam quality even under large pointing errors [15, 18]

7. CONCLUSION

This work successfully demonstrates that adaptive THz beam steering significantly enhances deep space communication links by overcoming the fundamental limitations of conventional fixed-beam systems. Through MATLAB simulation, the proposed closed-loop steering framework achieves superior channel capacity [1], [5] consistency, higher SNR across extended distances, and exceptional resilience to pointing errors. The results confirm that continuous beam alignment using SNR feedback effectively compensates for spacecraft vibrations, thermal drifts, and propagation-induced misalignments without requiring bulky mechanical gimbals or ultra-precise open-loop pointing. This adaptive approach paves the way for terabit-per-second deep space links, enabling future lunar, Mars, and interplanetary missions [12], [20] to transmit high-definition video, scientific telemetry, and autonomous navigation data with unprecedented reliability and efficiency.

REFERENCES

[1] C. Xie, Y. Liu, M. Elkashlan, and K. Wong, “Fast and Accurate Terahertz Beam Management via Frequency-Dependent Beamforming,” IEEE Transactions on Wireless Communications, vol. 22, no. 9, pp. 6153–6168, Sept. 2023.

[2] J. Li, H. Zhang, and Y. Zhao, “A Terahertz Band Transceiver with Agile Beam Steering,” in Proc. Int. Conf. Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Aug. 2021, pp. 1–2.

[3] L. Zhang, Z. Xiao, T. Zhou, and Y. Gao, “Vision-Aided Positioning and Beam Focusing for 6G Terahertz Communications,” IEEE Journal on Selected Areas in Communications, vol. 42, no. 9, pp. 2198–2212, Sept. 2024.

[4] A. Singh, P. K. Jain, and R. Kumar, “Terahertz Beam Steering: From Fundamentals to Applications,” J. Infrared, Millimeter, and Terahertz Waves, vol. 44, pp. 753–778, Mar. 2023.

DOI: 10.17148/IJIREEICE.2026.14603

[5] S. A. Busari, M. Z. Chowdhury, and J. Rodriguez, “Beam Alignment for mmWave and THz: Systematic Review,” Telecommunication Systems, vol. 82, pp. 105–129, Jan. 2025.

[6] M. Dragoman, A. Dinescu, and D. Neculoiu, “Terahertz Beam Steering Concept Based on a MEMS-Reconfigurable Reflection Grating,” *Sensors*, vol. 20, no. 10, pp. 2874–2884, May 2020.

[7] F. Zhang, S. Wu, and Y. Zhou, “Wideband Beam Steering Concept for Terahertz Time-Domain Spectroscopy,” *Sensors*, vol. 20, no. 19, pp. 5584–5592, Oct. 2020.

[8] Q. Wu, C. You, and R. Zhang, “Intelligent Reflecting Surface Assisted Terahertz Communications Toward 6G,” IEEE Wireless Communications, vol. 28, no. 6, pp. 110–117, Dec. 2021.

[9] M. Burla, A. Josten, and H. Finkelstein, “Mobile Terahertz Communications Using Photonic-Assisted Beam Steering Leaky-Wave Antennas,” *Optics Express*, vol. 29, no. 14, pp. 21985–21995, Jul. 2021.

[10] Y. Li, H. Chen, and S. Sun, “Terahertz Beam Steering Technologies: From Phased Arrays to Field-Programmable Metasurfaces,” *Advanced Optical Materials*, vol. 8, no. 4, pp. 1900628-1–1900628-16, Feb. 2020.

11] P. Sen, H. R. Amin, and J. M. Jornet, “Terahertz vs. Optical for Inter-Satellite Links: A Comparative Analysis of Pointing Errors and System Performance,” in *Proc. 2nd ACM/IEEE Workshop on THz Communications (THzCom)*, 2025, pp. 1–6.

[12] S. Liu, J. M. Jornet, and I. F. Akyildiz, “Channel Modeling for Terahertz Band Communication in Interplanetary Networks,” *IEEE Transactions on Communications*, vol. 69, no. 12, pp. 8585–8600, Dec. 2021.

[13] J. Ma, L. Mo, and T. S. Rappaport, “Kalman Filter Based Beam Tracking for Terahertz Communication in Non-Stationary Scenarios,” *IEEE Transactions on Wireless Communications*, vol. 22, no. 5, pp. 3123–3137, May 2023.

[14] C. Han, A. O. Bicen, and I. F. Akyildiz, “Multi-Ray Channel Modeling and Wideband Characterization for Terahertz Band Communication,” *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 5, pp. 1916–1928, May 2016.

[15] M. T. K. Sarker, M. H. A. Khan, and M. A. S. Bhuiyan, “Adaptive Beam Steering for Deep Space Terahertz Links Using Extended Kalman Filter,” in *Proc. IEEE International Conference on Space Mission Challenges for Information Technology (SMC-IT)*, 2024, pp. 45–52.

[16] R. Wang, Y. Xing, and T. S. Rappaport, “Terahertz Antennas and Beam Steering for CubeSat Deep Space Communications,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 38, no. 2, pp. 16–32, Feb. 2023.

[17] Z. Chen, J. Tan, and L. Dai, “Bayesian Learning Based Beam Tracking for Terahertz Communications Under Pointing Errors,” *IEEE Transactions on Communications*, vol. 71, no. 8, pp. 4723–4737, Aug. 2023.

[18] A. Masihi, P. Testolina, and J. M. Jornet, “Effect of Pointing Errors on Terahertz Inter-Satellite Links: A Statistical Channel Model,” in *Proc. IEEE Global Communications Conference (GLOBECOM)*, 2024, pp. 1–6.

[19] Y. Zhang, H. Lu, and C. Han, “Angle-of-Arrival Estimation and Kalman Tracking for Terahertz Deep Space Communication,” *IEEE Transactions on Terahertz Science and Technology*, vol. 14, no. 3, pp. 281–293, May 2024.

[20] S. U. H. Qazi, M. Z. Chowdhury, and J. M. Jornet, “THz/FSO Hybrid Links for Deep Space: Beam Steering and Pointing Error Compensation,” *IEEE Transactions on Communications*, vol. 73, no. 1, pp. 512–527, Jan. 2025.