

Reproducing and Extending a Joint Terahertz Communication and Sensing Link Budget: A Monte-Carlo Modulation Study

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Abstract—This report reproduces the physical-layer link-budget analysis of a joint communication and sensing (JCS) system operating in the terahertz (THz) band from a low Earth orbit (LEO) satellite, following the model of Aliaga *et al.* The downlink budget at 174.8 GHz is re-implemented in MATLAB, including atmospheric absorption, spreading loss, and the resulting bit energy-to-noise-density ratio (E_b/N_0) as a function of satellite elevation angle. As a small extension, a Monte-Carlo bit-error-rate (BER) simulator is built for BPSK and QPSK and verified against the analytic Q -function. The simulator is used to extract the required E_b/N_0 threshold at a target BER of 10^{-6} , which is then mapped back onto the link budget to identify the minimum usable elevation angle. The extracted threshold (10.47 dB) agrees with the analytic value (10.5 dB), confirming the correctness of the simulation pipeline.

Index Terms—Terahertz communications, joint communication and sensing, link budget, Monte-Carlo simulation, bit error rate, satellite communications.

I. INTRODUCTION

The terahertz band (0.1 THz to 1 THz) is a candidate for high-data-rate non-terrestrial networks in 6G, and the same hardware used for THz communication can also perform atmospheric remote sensing through Differential Absorption Radar (DAR) [1]. A joint communication and sensing (JCS) waveform based on Chirp Spread Spectrum (CSS) modulation can transmit information while simultaneously retrieving water-vapor profiles, at the cost of a lower data rate relative to conventional modulation.

This report has two goals. First, to *reproduce* the communication link budget of [1] for a LEO satellite downlink and confirm the reported trade-off between robustness and data rate across elevation angles. Second, to *extend* the analysis with a Monte-Carlo BER simulator that empirically determines the E_b/N_0 required by a given modulation to meet a target error rate, rather than relying solely on a closed-form expression. The motivation for the Monte-Carlo approach is that it generalizes naturally to higher-order modulations and to impaired channels where clean analytic BER expressions may not be available.

II. SYSTEM MODEL AND LINK BUDGET

The scenario is a bi-static DAR mounted on a LEO satellite at altitude $h = 200$ km, transmitting on the downlink to a

TABLE I
KEY SYSTEM PARAMETERS

Parameter	Value
Altitude, h	200 km
Transmit power, P_{tx}	200 mW
Transmit gain, G_{tx}	48 dB
Receive gain, G_{rx}	58 dB
Chirp bandwidth, B_{chirp}	60 MHz
Transmit frequency, f_3	174.8 GHz
Noise temperature, T_0	290 K
Noise figure	8 dB
Roll-off factor, α	0.35

ground station. The signal-to-noise ratio at the ground station is computed from the standard link-budget equation [2]

$$\text{SNR}(\theta, f_3) = P_{tx} G_{tx} \frac{1}{L(\theta, f_3)} \frac{G_{rx}}{T_0} \frac{1}{k B F_{gs}}, \quad (1)$$

where θ is the elevation angle and $f_3 = 174.8$ GHz is the highest-absorption transmit frequency considered. The total path loss $L = L_{spr} L_{abs}$ combines spreading loss and molecular absorption loss.

The absorption loss is obtained by numerically integrating the specific attenuation along the slant path. The atmosphere is sliced into $N = 1000$ layers from the surface to 84 km; temperature and pressure per layer are taken from a standard-atmosphere model, and the water-vapor density follows an exponential profile $\rho_v(h) = \rho_0 e^{-h/h_0}$ with $\rho_0 = 7.5 \text{ g/m}^3$ and $h_0 = 2$ km. The specific attenuation of each layer is evaluated with an ITU gaseous-attenuation model, and the slant contribution of each layer scales as $1/\sin \theta$.

For the communication figure of merit, the bit energy-to-noise-density ratio is used. For a conventional BPSK link,

$$\frac{E_b}{N_0} = \text{SNR} (1 + \alpha), \quad (2)$$

with roll-off $\alpha = 0.35$. For the CS-BPSK waveform, the processing gain (time-bandwidth product $B_{chirp} T_s$) raises the effective E_b/N_0 [1]:

$$\frac{E_b}{N_0} = \text{SNR} B_{chirp} T_s. \quad (3)$$

The key system parameters used are summarized in Table I.

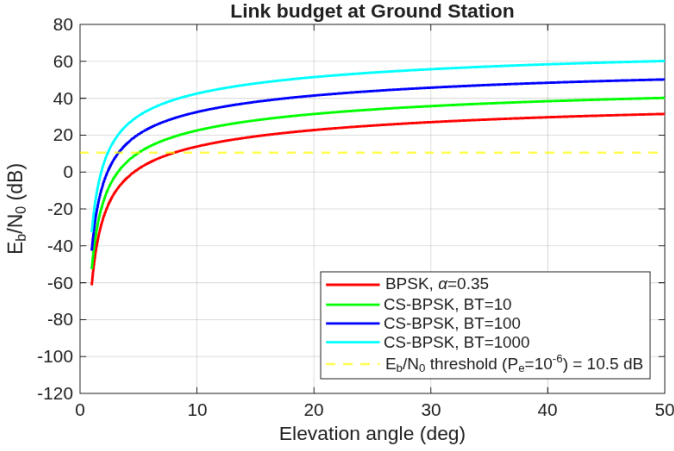


Fig. 1. Reproduced link budget: available E_b/N_0 versus elevation angle for BPSK and CS-BPSK at several time–bandwidth products. The dashed line is the E_b/N_0 required for $P_e = 10^{-6}$.

A. Reproduced Result

Figure 1 reproduces the link-budget behavior of [1]. The available E_b/N_0 increases with elevation angle, because higher elevation corresponds to a shorter slant path and therefore lower absorption and spreading loss. Increasing the CS-BPSK time–bandwidth product $B_{chirp}T_s$ shifts the curve upward, so the modulation crosses the link-quality threshold at a lower elevation angle. This widens the usable transmission window at the expense of symbol rate, reproducing the central robustness-versus-rate trade-off of the original paper.

III. EXTENSION: MONTE-CARLO BER AND THRESHOLD EXTRACTION

The link budget describes the *available* E_b/N_0 but not the value *required* by a given modulation to achieve reliable communication. To determine this empirically, a Monte-Carlo BER simulator was implemented.

A. Method

For each point on an E_b/N_0 sweep, N random bits are generated, mapped to symbols, corrupted by additive white Gaussian noise, and decoded; the BER is estimated as the fraction of decoded bits that differ from the transmitted bits. For BPSK, symbols are ± 1 and the decision rule is a sign test. For QPSK, two independent bit streams modulate the in-phase and quadrature axes of a complex symbol, which is equivalent to two parallel BPSK channels. The noise standard deviation for a target linear ratio (E_b/N_0) is set by

$$\sigma = \sqrt{\frac{1}{2(E_b/N_0)}}, \quad (4)$$

with E_b normalized to unity. Simulations used $N = 10^7$ bits per point over a sweep of 0 dB to 14 dB.

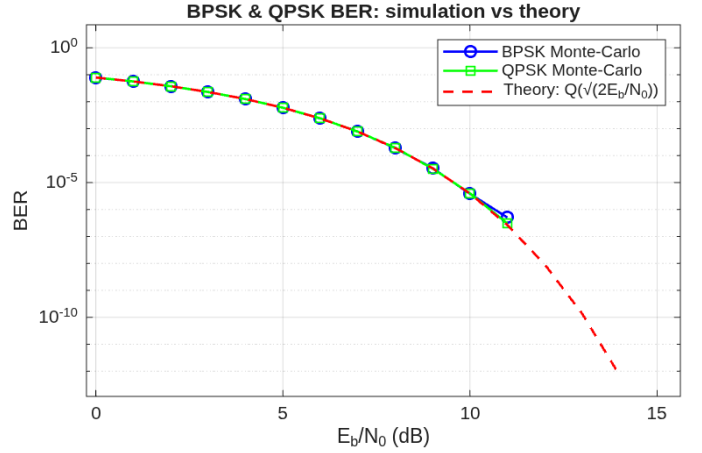


Fig. 2. Monte-Carlo BER versus E_b/N_0 for BPSK/QPSK compared with the analytic Q -function. Agreement validates the simulation pipeline.

B. Verification

Figure 2 compares the simulated BER against the analytic expression $P_b = Q(\sqrt{2E_b/N_0})$. The Monte-Carlo points lie on the analytic curve for both BPSK and QPSK, confirming both the noise scaling and the expected result that QPSK achieves the same per-bit reliability as BPSK while carrying twice the bits per symbol. At the low-BER end, the simulated curve departs from theory only where too few error events are captured for a reliable estimate, consistent with the statistics of rare-event counting.

C. Threshold Extraction and Mapping to Elevation

The required E_b/N_0 at a target BER of 10^{-6} was extracted from the simulated curve by interpolating in $\log_{10}(\text{BER})$ space. The Monte-Carlo estimate was 10.47 dB, in close agreement with the analytic threshold of 10.5 dB obtained from Q^{-1} . When this threshold is drawn on the reproduced link budget, its intersection with the channel curve defines the minimum elevation angle at which that modulation closes the link. This connects the two halves of the analysis: the Monte-Carlo simulation supplies the required E_b/N_0 , and the link budget supplies the available E_b/N_0 as a function of geometry.

IV. DISCUSSION AND LIMITATIONS

The agreement between the simulated and analytic thresholds is expected for BPSK and QPSK, where the analytic BER is exact; the value of the Monte-Carlo framework is that it extends to cases without a convenient closed form, such as higher-order or amplitude/phase-shift-keyed constellations, and to non-ideal channels. The present study is limited to an additive white Gaussian noise channel and does not model amplifier non-linearity, phase noise, or fading, all of which are relevant to real THz satellite front-ends and to the higher-order modulations used in standards such as DVB-S2. The sensing (DAR) side of the JCS waveform is not treated here; only the communication link budget is reproduced.

V. CONCLUSION

The communication link budget of a THz JCS LEO down-link was reproduced, confirming the reported robustness-versus-rate trade-off across elevation angle. A Monte-Carlo BER simulator for BPSK and QPSK was implemented, verified against theory, and used to extract the E_b/N_0 required at a target BER, which was then mapped onto the link budget to identify the minimum usable elevation angle. The close match between the simulated and analytic thresholds validates the approach and provides a foundation for extending the study to higher-order modulations and impaired channels.

REFERENCES

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