Analysis of the Effect of Beam Tracking Errors in sub-THz Inter-Satellite Communications

Chang Kyung Sung*, Hajime Suzuki*, Wei Ni*, Jia Du† and Ting Zhang†

*Data61, CSIRO, Sydney, Australia
†Manufacturing, CSIRO, Sydney Australia
Email: *chang.sung@csiro.au, hajime.suzuki@csiro.au, †jia.du@csiro.au, ting.zhang@csiro.au

***Abstract*—Tera-hertz band provides wider spectrum availability, but, to fully exploit the benefit, sensitivity to beam alignment and tracking need to be identified. In this paper, we analyze the link budget to identify the effect of beam tracking performance and transmit power restriction imposed by power amplifier. The analysis shows that proper channel coding is required to improve the communication distance and mitigate the effect of tracking errors. Also, for coded transmission, if the beam direction tracking is perfect, 215 GHz band achieves similar communication distance** as 100 GHz**,** whereas **if tracking errors are present** then **215 GHz** is found to be more error prone.

I. Introduction

In this paper, we analyze the link budget in sub-terahertz (THz) inter-satellite communications and identify factors to achieve high spectral efficiency and long range communications. In the sub-THz communication, higher gain antenna is demanded to increase system capacity by reducing path-loss between the inter-satellite link. However, the beamwidth becomes narrower as the antenna gain increases. For example, the antenna beamwidth is 1.7 degrees for a 40 dB antenna while the beamwidth is decreased into 0.105 for a 70 dB antenna [1]. In [2], it has been shown that

- For a fixed frequency, the increase of the tracking error of the transmitter gradually reduces the received power.
- For the same tracking-pointing error of the transmitter, when frequency becomes higher, the tracking error gives more serious impact on the received signal strength.

These observations lead us to study the effect of beam tracking error and signal processing technologies to mitigate the performance degradation. In this paper, we will show that proper channel coding is required to improve the communication distance and mitigate the effect of tracking errors. The channel coding gain has been observed to be much higher in 215 GHz compared to lower 100GHz band. For coded transmission, to achieve the same throughput, if the beam direction tracking is perfect, 215 GHz band achieves similar communication distance. If tracking errors are presented, 215 GHz has been shown to be more sensitive to the tracking error.

II. THz Link Budget

Free-space propagation is modelled as

$$P_r = P_t + 10\log(G_tG_r) - L(f,d)\text{in dB} \tag{1}$$

where $L(d,f)$ is the propagation loss computed by $L(d,f) = 20\log(4\pi f d/c)$ Here, f is the carrier frequency in Hz, d is the distance between two satellites, and c is the speed of light. As shown in the equation, the higher the frequency, the attenuation caused by the path-loss increases. The antenna gain is computed by $G = 4\pi^2 D_a^2/\lambda^2$ where λ is the wavelength and D_a is the antenna diameter. Then, the received power can be presented by $P_r = P_t + 20\log\left(\frac{\pi D_a^T D_a^R f}{c\times d}\right)$ in dB. We note that, for fixed antenna gain in (1), the receive power is inversely proportional to the frequency while the receive power increases proportional to the frequency for a fixed antenna diameter.

The signal power loss caused by the tracking and pointing error of the transmitter $A_t(\Phi)$ and receiver $A_r(\phi)$ can be represented by [2]

$$A_t(\Psi) = \exp\left(-\frac{8\Psi^2}{\theta_0^2}\right) \text{ and } A_r(\phi) = \cos(\phi), \tag{2}$$

respectively, where Ψ is the tracking-pointing error of the transmitter in μrad, ϕ is the tracking-pointing error in the receiver in μrad, and the main beamwidth θ_0 in μrad is obtained by $\theta_0 \approx 1.03\lambda/D_a$. By including tracking errors, the free-space propagation can be revised into

$$P_r = P_t + 10\log(G_tG_r) - L(f,d) - 10\log(A_t(\Psi)A_r(\phi))\text{in dB}$$

III. Link Budget Analysis

For the link budget analysis, we compare bit error rate (BER) for uncoded and coded transmission. In this paper, we employ Quadratic Amplitude Modulation (QAM) and convolutional channel coding with bit-level interleaver for coded modulation. For uncoded M-QAM, the BER can be approximated by $P_b \approx \frac{4}{\log_2 M} Q\left(\sqrt{\frac{2\bar{\gamma}_b \log_2 M}{M-1}}\right)$.

In practical communications, channel coding is a powerful tool to improve the performance. To obtain various rate convolutional code, we employ rate compatible punctured convolutional codes (RCPC) with puncturing period p. In this case, the instantaneous BER can be estimated as $P_b \leq \frac{1}{p}\sum_{d=d_H}^{d_H+5} N(d)P(d,H)$ where $N(d)$ denotes the total input weight of error events at Hamming distance d, and $P(d,H)$ represents the average code word pairwise error probability (PEP) between the code words having Hamming distance d. The list of $N(d)$ for various rates of convolutional codes can be found in [3]. For the calculation of PEP, we use the approach based on Bhattacharyya bound [3]. In this case, $P(d,H) \leq Q(\sqrt{-2d\ln B_M(H)})$ Here, $B_M(H)$ can be approximated for M-QAM by

M	$B_M(H)$
4	$Q_1 + Q_2$
16	$\frac{3}{8}(2Q_1 + 3Q_2)$
64	$\frac{1}{48}(28Q_1 + 49Q_2)$

where $Q_1 = Q\left(\sqrt{\frac{6}{4(M-1)}\gamma_s}\right)$ and $Q_2 = Q\left(\sqrt{\frac{3}{(M-1)}\gamma_s}\right)$.

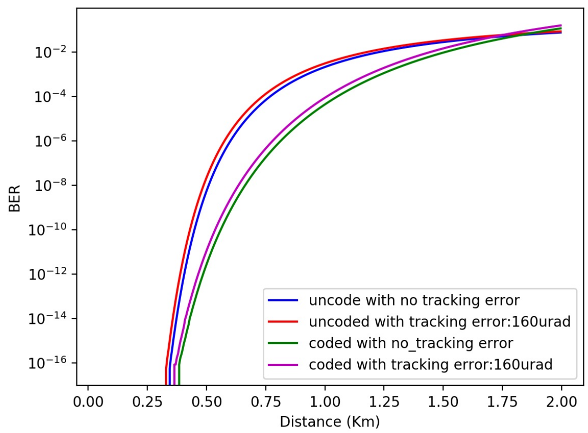

Fig. 1. BER with 4bps/Hz at 100GHz

Fig. 1 plots the BER curve with 4b/Hz at 100 GHz when the antenna with 2m diameter. In this frequency band, the effect of tracking error can be observed, but the effect can be considered as minimal. However, the benefit of channel coding can be observed to be significant.

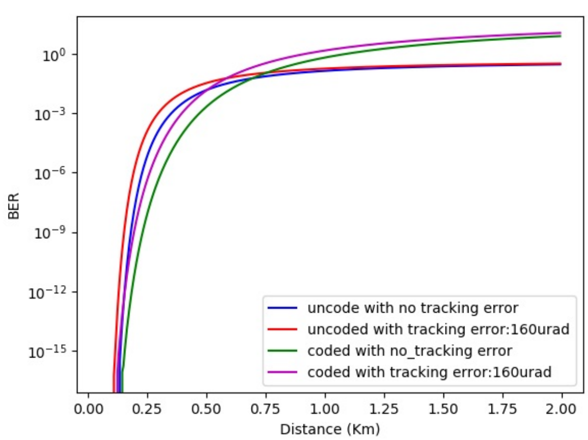

Fig. 2. BER with 4bps/Hz at 200GHz

Fig. 2 plots the BER curve with 4b/Hz at 0.2 THz when the antenna with 2m diameter. In this figure, we can observe the effect of tracking errors are more significant than that in Fig. 1 and see clearly the benefit of channel coding. When channel coding is applied, the BER performance with tracking error outperforms the uncoded transmission without tracking error.

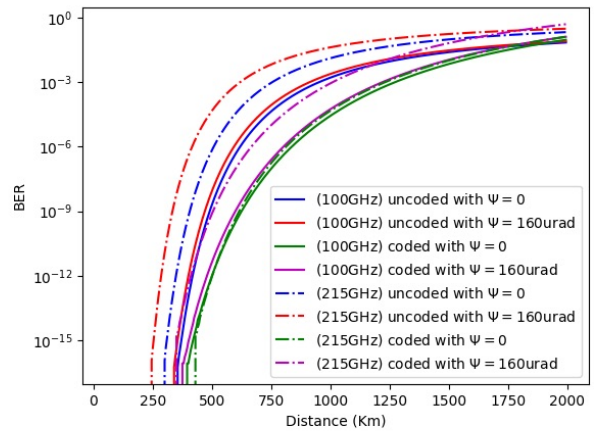

Fig. 3. BER to achieve 20Gbps

We now compare the communication distance at 100GHz and 215GHz frequencies. To ensure it operates in the linear region, TX output power largely depends on the saturation power/P1dB compression power of the power amplifier at relevant frequencies. Based on this front-end hardware configuration, we compare 100GHz and 215GHz using the following profiles.

Frequent (GHz)	100	215
Bandwidth (GHz)	10	20
TX power (dBm)	20	10
Rx noise temperature (K)	290	1000

So, for fair comparison, we compare the communication distance that can deliver 20Gps throughput which is equivalent to 4bit/Hz at 100 GHz and 2bits/Hz at 215 GHz. As shown in Fig. 3, when no beam tracking error is presented, if channel coding is applied, both 100 GHz and 200 GHz bands achieve similar error performance while, in uncoded case, the 100 GHz band outperforms the 215 GHz band. However, when tracking errors are presented, the performance degradation is more severe at 215GHz band even channel coding is applied.

References

[1] S. U. Hwu, K. B. deSilva, and C. T. Jih, "Terahertz (THz) wireless systems for space applications," in *Proc. of IEEE Sensors Application Symposium*, 2013.

[2] Y. Ding, X. Shi, S. Gao, H. Wu, and R. Zhang, "Analysis of tracking-pointing error and platform vibration effect in inter-satellite terahertz communication system," in *Proc. of Chinese Automation Congress*, 2017.

[3] C. K. Sung, S.-Y. Chung, J. Heo, and I. Lee, "Adaptive Bit-Interleaved Coded OFDM with Reduced Feedback Information," *IEEE Trans. Commun.*, vol. 55, Sep. 2007.