# Standardizing Performance Metrics for Submarine Transmission Paths

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**Abstract:** This paper describes the progress and obstacles towards defining a universal performance metric for ultralong haul submarine transmission paths. Sources of error and quantitative assessment of capacity prediction is also addressed.

## 1. Introduction

Historically, submarine transmission systems were provided in a turnkey solution that included both the dry- and wet-plant technologies. The advent of coherent modems and highly flexible submarine line terminal equipment (SLTE) have dramatically simplified capacity deployment and optimization of the dry-plant portion of submarine networks. Consequently, this initiated a split between dry and wet technology giving operators the freedom to choose best-in-breed SLTE and submarine cable vendors independently. This "open cable" paradigm [1] formed disparate measures of performance indicators [2] as wet-plants were no longer qualified by capacity potential or modem Q-factors, but rather variants of signal-to-noise ratio (SNR), for example; OSNR, GOSNR, or SNRe [3-5]. Network owners of submarine transmission systems are now responsible for ensuring these SNR-based parameters are adequate for their capacity demands and the modem vendor's requirements. Hence, Standards bodies play an important role for setting international guidelines for the assessment of submarine line terminal equipment, particularly ones that implement performance parameters useful for both modem and wet-plant vendors. This paper explores a variety of metrics used in the industry, their application space, sources of error, and a path to Standardization.

## 2. Performance Metrics

### *1.1. Overview*

The capacity of a transmission system depends on its spectral bandwidth and total SNR as defined by the Shannon capacity [6]. Shannon's original approach to communication theory was derived from the information entropy of the communication channel, where knowledge of all possible input distributions was known [7,8]. This paper focuses on hard-decision metrics which exist in Standards and/or are reported by real-time optical modems, hence stochastic formalisms such as mutual information and its extended models [9] are not covered.

### *1.2. BER and Q*

A fundamental measure of performance over a submarine transmission path is the pre-forward error correction (Pre-FEC) bit error ratio (BER) expressed as a Q-factor:

$$Q = \sqrt{2}\mathrm{erfc}^{-1}(2\mathrm{BER}) \tag{1}$$

Conventional Q-based optical power budgets, such as the examples defined in ITU-T G.977, rely on the back-to-back Q value at the link delivered OSNR, to which optical nonlinear and other modem impairments are added. Each impairment is modeled or measured as an equivalent (O)SNR penalty, thus the power budget process requires comprehensive tracking of the Q vs (O)SNR slope as a function of propagation. Table 1 is an example of the relationships between BER, Q, and SNR for several modulation formats under the assumptions of Gray encoding and high SNR so that off-axis bit error probabilities are negligible [10-12]. The empirical relationships for BPSK and QPSK between Q and SNR are the foundations to why and how Q-based optical budgets were formulated, that is, the Q-factor served as an accurate proxy for SNR.

| Modulation | BER | Q |
|---|---|---|
| BPSK | $\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\mathrm{SNR}}\right)$ | $\mathrm{Q} = \sqrt{2\mathrm{SNR}}$ |
| QPSK | $\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\mathrm{SNR}/2}\right)$ | $\mathrm{Q} = \sqrt{\mathrm{SNR}}$ |
| 16PSK | $\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left[\sqrt{\mathrm{SNR}}\sin\left(\frac{\pi}{16}\right)\right]$ | $\mathrm{Q} = \sqrt{2\mathrm{SNR}}\sin\left(\frac{\pi}{16}\right)$ |
| 16QAM | $\mathrm{BER} = \frac{3}{8}\mathrm{erfc}\left(\sqrt{2\mathrm{SNR}/5}\right)$ | $Q = \sqrt{2}\mathrm{erfc}^{-1}\left[\frac{3}{4}\mathrm{erfc}\left(\sqrt{2\mathrm{SNR}/5}\right)\right]$ |

Table 1. SNR to BER and Q relationships for different modulations assuming nearest neighbour Gray encoded constellations for high SNR.

### *1.3. SNR and eSNR*

Recent advancements in coherent optical technologies embrace higher constellation cardinality, stronger FEC engines that operate at very low SNR, and novel bit-to-symbol encoding formats [13,14] which no longer hold a closed form analytical solution for BER (or Q) as a function of SNR. Subsequently, the BER for each modulation format at a given SNR is achieved through widely used numerical techniques such as the Monte-Carlo method [15]. The technique passes N data symbols through a model of the modem and the SNR is varied by injecting pseudo random noise along the data path. The symbols are decoded by the simulator and the bit errors counted to estimate the BER.

When a BER to SNR relationship (and vice versa) has been formed, the behavior of a modem's performance in the presence of receiver optical noise loading can be expressed:

$$\frac{1}{SNR} = \frac{1}{SNR_{ase}} + \frac{1}{SNR_m} \tag{2}$$

Where the total $SNR$ is a function of the equivalent BER, and $SNR_{ase}$ is the OSNR normalized to the noise bandwidth of the channel, that is, the linear optical noise from amplified spontaneous emission (ASE). $SNR_m$ is the back-to-back modem implementation noise. Optically noise loaded modems typically do not produce a relation identical to Equation (2) when the BER is translated to $SNR$, but the relationship is often scaled by a constant factor known here as $\epsilon$ [16]. We refer to this scaling of the $SNR$ as $eSNR$:

$$\frac{1}{eSNR} = \epsilon\left(\frac{1}{SNR_{ase}} + \frac{1}{SNR_m}\right) \tag{3}$$

Required $SNR_{ase}$ or $RSNR_{ase}$ refers to the minimum $SNR_{ase}$ that results in error free traffic, hence the associated minimum $eSNR$ becomes the $ReSNR$. Accurate capacity assessment in the absence of field trials requires detailed knowledge of $\epsilon$, $SNR_m$, $RSNR_{ase}$, and the $ReSNR$ in the presence of polarization effects, electronic dispersion compensation, laser phase noise [17], and other modem-line coupled distortions. These large arrays of parameters are used to perform optical link budgeting during the design phase of submarine transmission systems. The final system commissioning is thus required to meet the link budget parameters set at the design phase.

### *1.4. Generalized SNR (GSNR)*

The GSNR was introduced as a modeling concept where the effects of nonlinear propagation could be approximated as excess additive Gaussian noise [18]. It strictly pertains to the sum of noise contributions by ASE and optical nonlinearity:

$$\frac{1}{GSNR} = \frac{1}{SNR_{ase}} + \frac{1}{SNR_{nl}} \tag{4}$$

Where $SNR_{nl}$ is the signal-to-noise ratio of all optical nonlinear contributions. In the open cable model, GSNR serves as a key performance indicator of submarine transmission systems in the absence of a coherent modem. Systems may be qualified based on a value averaged across the spectrum of interest. However, due to the challenges of removing modem-line coupled impairments experimentally, GSNR is typically accompanied by an equivalent ITU-T G.977 power budget table defining the estimated modem contributions that were removed. However, the GSNR may be coupled with a series of eSNR measurements to reveal the nonlinear performance and the effects of modem-line impairments on its estimation.

### *1.5. SNR Budgeting*

A method of performing optical link budgeting is presented to determine the net system margin of a channel. The SNR parameters described earlier will be explored as a function of modulation and propagation conditions to determine the capacity potential of a submarine transmission system. The accuracy of such capacity predictions is subject to several variances that may be dry- or wet-plant related. As a result, system commissioning on a channel-by-channel basis can be challenging when validated against a simulated optical power budget.

## 3. Conclusion

We review a path to defining SNR performance metrics to assess the capacity and evaluate sources of error in the absence of field trials.

## 4. References


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