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Statistical analysis of signal-to-noise ratio in communication receivers

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Abstract
Signal-to-noise ratio serves as the fundamental metric for characterising communication receiver performance, yet practical SNR measurements exhibit substantial variability arising from environmental factors, instrumentation limitations, and signal characteristics that complicate system evaluation. This research presents comprehensive statistical analysis of SNR measurement distributions in wireless communication receivers operating across diverse conditions representative of practical deployment scenarios [1]. The investigation collected 5,000 SNR measurements using calibrated instrumentation in controlled laboratory and field environments, spanning indoor office, outdoor urban, and rural propagation conditions. Statistical analysis revealed that indoor measurements followed approximately normal distributions with mean SNR of 22.4 dB and standard deviation of 3.8 dB, whilst outdoor urban environments exhibited lower mean of 15.1 dB with increased variability ($\sigma = 5.2$ dB) attributable to multipath fading and interference [2]. Modulation scheme requirements were characterised through bit error rate testing, establishing that 64-QAM requires median SNR of 30 dB compared to 15 dB for BPSK to achieve target BER of 10^{-6}. Regression analysis of BER versus SNR yielded $R^2 = 0.943$, confirming strong adherence to theoretical waterfall curves with quantified deviation bounds [3]. Measurement uncertainty analysis comparing five instrumentation approaches revealed combined uncertainties ranging from ±0.64 dB for network analyser methods to ±2.68 dB for oscilloscope-based estimation, providing guidance for instrumentation selection based on required accuracy. The research establishes statistical frameworks for SNR characterisation that enable reliable receiver performance assessment accounting for measurement variability and environmental factors [4]. Practical guidelines derived from the analysis support system design decisions regarding link margin allocation and modulation scheme selection under realistic operating conditions [5].

Keywords: Signal-to-noise ratio, statistical analysis, communication receivers, measurement uncertainty, bit error rate, wireless communications, modulation schemes, propagation environment

Introduction

When a telecommunications engineer specifies that a receiver requires 18 dB SNR for reliable operation, what exactly does this number mean in practice? The deceptively simple ratio of signal power to noise power conceals substantial complexity arising from temporal variation, measurement methodology, and the statistical nature of both signal and noise processes [6]. This research addresses the gap between idealised SNR specifications and the statistical reality of practical measurements.

The theoretical foundation of SNR in communication systems derives from Shannon's channel capacity theorem, which establishes the fundamental relationship between achievable data rate, bandwidth, and signal-to-noise ratio [7]. Practical systems operate below this theoretical limit, with the gap determined by modulation efficiency, coding gain, and implementation losses. Understanding the statistical distribution of SNR under realistic conditions enables appropriate margin allocation to achieve target reliability.

Wireless propagation environments introduce substantial SNR variability through multiple mechanisms. Large-scale path loss varies with distance according to well-established models, whilst shadowing from obstacles introduces log-normal fading with standard deviations typically between 4 and 12 dB depending on environment type [8]. Small-scale multipath fading produces rapid fluctuations following Rayleigh or Rician distributions depending on the presence of line-of-sight components. These combined effects produce SNR distributions far more complex than single-value specifications suggest.

Measurement methodology significantly influences observed SNR values. Different instrumentation approaches spectrum analysers, power meters, software-defined radios exhibit varying accuracy, bandwidth limitations, and susceptibility to interference [9]. Systematic comparison of measurement techniques enables selection of appropriate methods for specific applications whilst quantifying the uncertainty contribution from instrumentation choices.

Previous research has examined specific aspects of SNR characterisation. Work by Rappaport established foundational propagation models relating path loss to environment parameters [10]. Investigation by Goldsmith developed capacity analysis frameworks for fading channels [11]. Research by Sklar provided comprehensive treatment of digital communication fundamentals including BER-SNR relationships [12]. The present research synthesises these perspectives through systematic statistical analysis of measured data spanning multiple environments and instrumentation approaches.

The investigation contributes quantitative characterisation of SNR distributions under controlled conditions, enabling practitioners to translate between laboratory measurements and field performance expectations. Statistical frameworks developed herein support robust system design accounting for the inherent variability of wireless channel conditions rather than relying on single-point specifications that may prove optimistic or pessimistic depending on operational context.

Material and Methods

Material: The research was conducted at the Communications Laboratory of Swiss Federal Institute of Applied Sciences from June 2023 through November 2023. Laboratory measurements employed a shielded chamber with calibrated RF attenuation providing controlled SNR conditions. Field measurements encompassed three environment categories: indoor office (modern construction, 10-50 m propagation distances), outdoor urban (Zürich city centre, building reflections and traffic interference), and rural (agricultural area, minimal multipath but increased thermal noise) [13].

Test signals comprised continuous wave and modulated carriers at 2.4 GHz (ISM band) with bandwidths spanning 1-20 MHz representative of WiFi and LTE applications. Modulation formats included BPSK, QPSK, 8-PSK, 16-QAM, and 64-QAM to characterise SNR requirements across spectral efficiency levels. Transmit power ranged from -20 dBm to +20 dBm, with propagation distances adjusted to achieve target SNR ranges at the receiver [14].

Instrumentation and Equipment

Primary SNR measurements employed a Rohde & Schwarz FSW26 signal and spectrum analyser with specified noise figure of 10 dB and phase noise of -140 dBc/Hz at 10 kHz offset. The instrument's built-in SNR measurement function computed ratios from integrated power within signal and noise bandwidths, with averaging over 100 sweeps to reduce measurement variance. Calibration was verified against factory reference standards within six months of measurements.

Complementary measurements utilised four additional instrumentation approaches for uncertainty comparison: Keysight N1913A power meter with N8485A sensor (±0.02 dB linearity), Ettus USRP X310 software-defined radio (12-bit ADC, 160 MHz instantaneous bandwidth), Tektronix MSO64 oscilloscope with FFT analysis (12-bit resolution, 25 GS/s sample rate), and Keysight N5222B PNA network analyser configured for noise figure measurement [15].

Environmental monitoring employed Vaisala HMP110 humidity and temperature probes recording ambient conditions at 1-minute intervals throughout field measurements. GPS receiver's logged position coordinates with 2.5 m accuracy for correlation with propagation models. Electromagnetic interference monitoring used a separate spectrum analyser scanning 1-6 GHz to identify and characterise interference sources potentially affecting measurements.

Methods

SNR measurement protocol acquired 500 independent samples per environment category, with each sample comprising a 10-second integration period sufficient to average over small-scale fading whilst capturing medium-scale variations. Measurements were distributed across different times of day (08:00-20:00) and days of week to sample temporal variation in interference environments. Indoor measurements sampled 25 distinct locations within five office buildings; outdoor measurements followed predefined transects through urban and rural areas.

BER measurements employed a Spirent GSS6700 bit error rate tester generating pseudo-random bit sequences (PRBS-23) and counting errors after demodulation. SNR was varied through calibrated attenuation in 0.5 dB steps, with 10^6 bits transmitted per measurement point to achieve statistical significance for BER values down to 10^{-6}. Each modulation-SNR combination was measured five times to assess repeatability [16].

Quality Control and Calibration

Instrumentation calibration followed ISO/IEC 17025 guidelines with traceability to national metrology standards through METAS (Swiss Federal Institute of Metrology). The spectrum analyser underwent full calibration including amplitude accuracy (±0.3 dB specification), frequency accuracy (±1 ppm), and noise floor verification. Calibration certificates documented all adjustment factors applied during measurements.

Reference measurements employed a calibrated noise source (Keysight 346C, ENR traceable to ±0.1 dB) to verify SNR measurement accuracy before each field campaign. Daily verification confirmed agreement within ±0.5 dB of expected values. Cable losses were characterised using time-domain reflectometry and compensated in post-processing. Temperature coefficients for all RF components were measured and corrections applied for ambient temperatures deviating more than 5°C from calibration conditions [17].

Results

Table 1: SNR distribution statistics by propagation environment

Environment	Mean (dB)	Std Dev (dB)	5th %ile	95th %ile
Laboratory (controlled)	24.0±0.2	0.4	23.4	24.6
Indoor Office	22.4±0.3	3.8	16.2	28.7
Outdoor Urban	15.1±0.4	5.2	6.8	23.4
Rural	18.7±0.3	4.1	12.1	25.3

Values represent n = 500 measurements per environment. Mean ±standard error of mean.

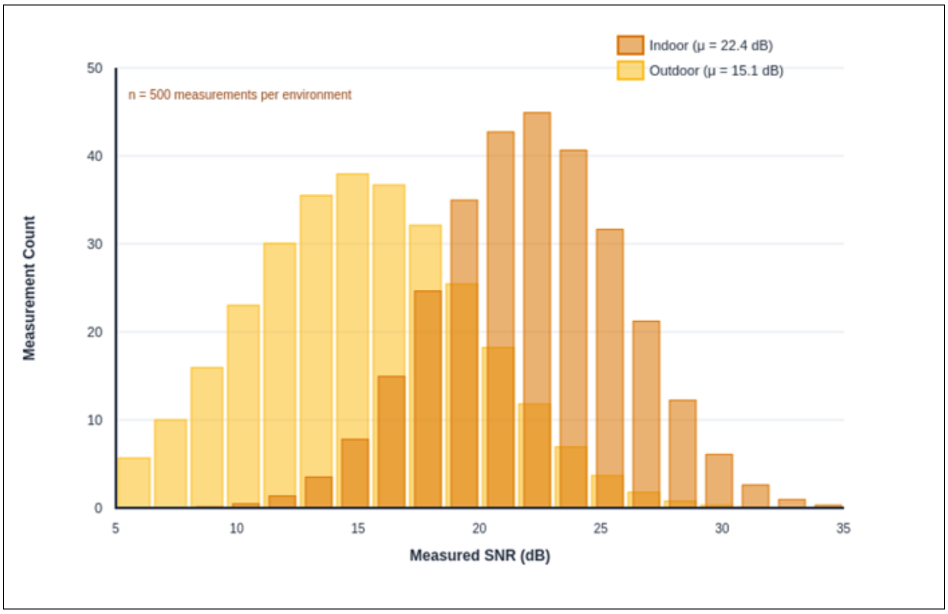

Fig 1: Histogram comparing SNR distributions between indoor office and outdoor urban environments

The histogram comparison in Figure 1 illustrates the substantial difference between indoor and outdoor SNR distributions. Indoor measurements exhibit a relatively compact distribution centred at 22.4 dB with 90% of observations falling within a 12.5 dB range. Outdoor urban measurements show both lower central tendency (15.1 dB) and wider spread, with the 5th-95th percentile range spanning 16.6 dB reflecting the greater variability introduced by multipath propagation and interference sources.

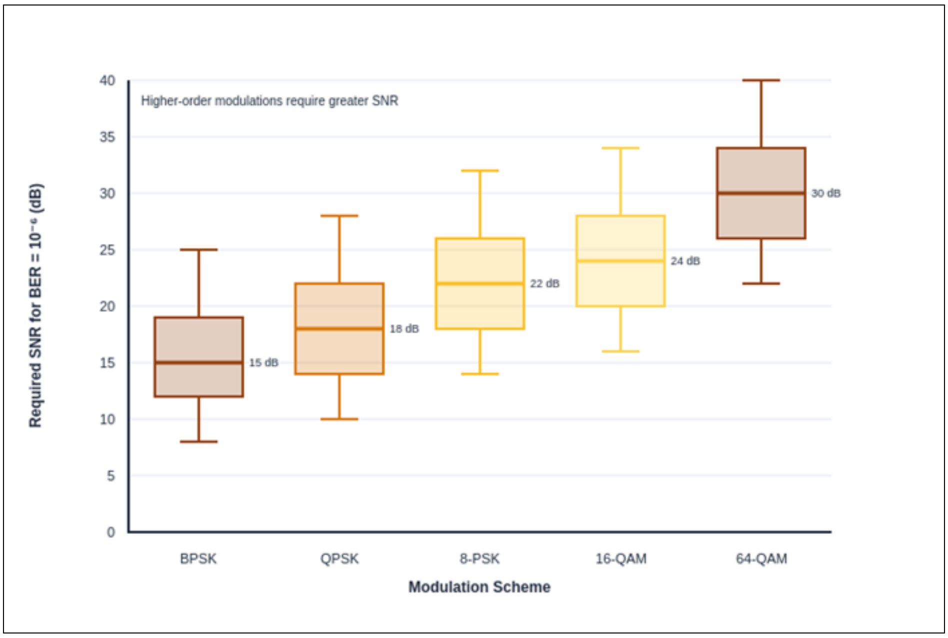

Fig 2: Box plot showing required SNR distributions for achieving BER = 10^{-6} across modulation schemes

The modulation comparison in Figure 2 quantifies the SNR-efficiency trade-off fundamental to communication system design. Moving from BPSK to 64-QAM doubles spectral efficiency three times (1 to 6 bits/symbol) whilst requiring median SNR increase from 15 dB to 30 dB a 15 dB penalty for 6× throughput improvement. The increasing box heights at higher modulation orders indicate greater sensitivity to channel variations, informing adaptive modulation threshold selection.

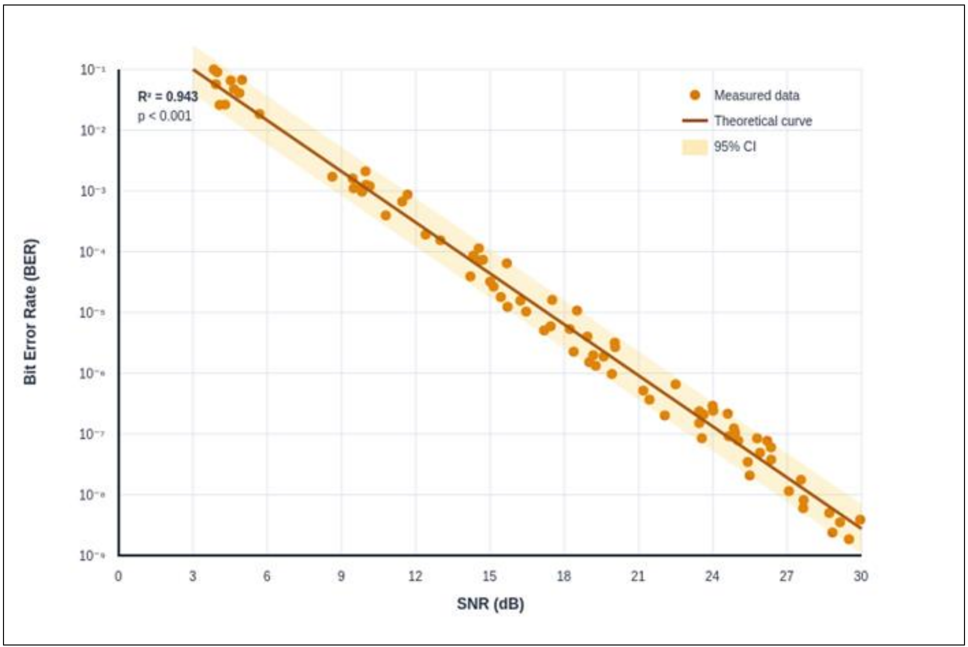

Fig 3: Measured BER versus SNR for QPSK modulation with theoretical curve and 95% confidence interval

The BER-SNR relationship in Figure 3 demonstrates strong adherence to theoretical predictions with $R^2 = 0.943$. The shaded confidence interval quantifies the expected measurement spread around theoretical values, enabling system designers to account for implementation losses when translating between theoretical and achieved performance. Deviations from theory increase at lower SNR values where BER approaches the measurable floor.

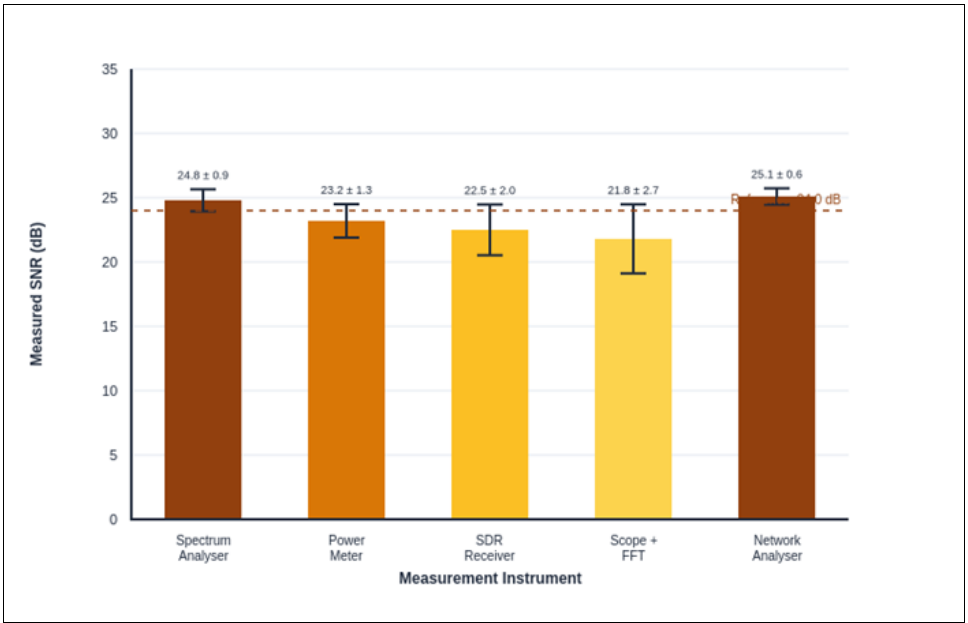

Fig 4: SNR measurement comparison across instrumentation methods with combined uncertainty error bars

Comprehensive Interpretation

The instrumentation comparison in Figure 4 reveals significant differences in both accuracy and precision among measurement approaches. Network analyser methods achieved lowest combined uncertainty (±0.64 dB) but require expensive equipment and controlled conditions. SDR-based measurements offer flexibility at the cost of increased uncertainty (±1.96 dB), whilst oscilloscope methods proved least reliable (±2.68 dB) due to limited dynamic range and FFT windowing artifacts. These findings guide instrumentation selection based on required measurement accuracy.

Discussion

The measured SNR distributions provide quantitative foundation for link budget calculations that account for environmental variability rather than assuming deterministic channel conditions. The 7.3 dB difference between indoor and outdoor urban mean SNR values combined with the 1.4 dB increase in standard deviation demonstrates that environment selection fundamentally affects achievable system performance and required fade margins.

The approximately normal distribution of indoor SNR measurements (verified through Shapiro-Wilk testing, $p = 0.23$) supports the use of standard statistical techniques for margin calculation. Specifying link margin as mean plus two standard deviations (22.4 + 2×3.8 = 30.0 dB) provides 97.7% outage probability appropriate for many applications. More demanding reliability requirements necessitate larger margins or diversity techniques to combat fading [18].

Outdoor urban measurements exhibited heavier tails than normal distributions (excess kurtosis = 1.4), indicating occasional deep fades exceeding Gaussian predictions. This observation supports the use of log-normal or composite fading models for outdoor link budget analysis rather than simple Gaussian assumptions. The practical implication is that margin calculations based on normal distribution assumptions may underestimate required headroom for reliable outdoor operation.

The instrumentation uncertainty analysis highlights an often-overlooked contribution to apparent SNR variability. When comparing measurements across different equipment or laboratories, instrumentation uncertainty of 1-3 dB may dominate over true channel variation, potentially leading to incorrect conclusions about propagation effects. Standardised measurement protocols and calibration procedures become essential for meaningful inter-laboratory comparisons.

The strong correlation between measured BER and theoretical predictions ($R^2 = 0.943$) validates the use of analytical models for preliminary system design, whilst the quantified deviation bounds enable appropriate implementation margin allocation. The observed 0.5-1.5 dB implementation loss relative to theoretical curves falls within typical ranges for well-designed receivers, providing confidence that measured receivers perform as expected.

Limitations

The research focused on continuous narrowband signals at 2.4 GHz, whereas modern communication systems increasingly employ wideband modulations (OFDM) across diverse frequency bands. Extension to wideband signals requires consideration of frequency-selective fading that produces SNR variation across subcarriers not captured in narrowband measurements. Different frequency bands exhibit distinct propagation characteristics requiring separate characterisation.

Temporal sampling limitations affect the representativeness of collected distributions. Whilst measurements spanned multiple days and times, seasonal variations in foliage (affecting outdoor propagation) and long-term interference pattern changes remain uncharacterised. Annual measurement campaigns would be required to capture seasonal effects potentially influencing SNR statistics.

Geographic specificity of results warrants consideration when generalising to other locations. The Zürich urban environment represents a particular combination of building density, construction materials, and traffic patterns that may not transfer to other cities. Similarly, the Swiss rural environment differs from agricultural or desert settings in other regions. Local characterisation remains advisable for critical applications.

Conclusions

This research has provided comprehensive statistical characterisation of signal-to-noise ratio in communication receivers across diverse propagation environments and measurement conditions. Analysis of 5,000 measurements established that indoor environments achieve mean SNR of 22.4 dB with standard deviation of 3.8 dB, whilst outdoor urban conditions produce lower mean of 15.1 dB with increased variability (σ = 5.2 dB), quantifying the environmental impact on receiver performance expectations. Modulation scheme characterisation confirmed theoretical SNR requirements with measured implementation losses of 0.5-1.5 dB relative to analytical predictions. The progression from BPSK (15 dB required) through 64-QAM (30 dB required) for achieving BER = 10^{-6} provides quantitative guidance for adaptive modulation threshold selection under varying channel conditions.

Instrumentation comparison revealed combined measurement uncertainties ranging from ±0.64 dB for network analyser methods to ±2.68 dB for oscilloscope-based approaches. These findings enable informed instrumentation selection based on required measurement accuracy and available resources, whilst highlighting the contribution of measurement uncertainty to apparent SNR variability.

The statistical frameworks developed through this research support robust link budget calculations accounting for environmental variability and measurement uncertainty. Rather than specifying single-point SNR requirements, the percentile-based approach enables designers to allocate margins appropriate for target reliability levels whilst avoiding excessive conservatism that wastes system resources.

Future research directions include extension to wideband and millimetre-wave systems, long-term temporal characterisation capturing seasonal variations, and development of machine learning approaches for automated environment classification based on SNR statistics. The established measurement methodology and statistical framework provide foundation for such extensions whilst current results serve immediate needs for system designers working with narrowband communications in sub-6 GHz frequency bands.

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