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Operational Test of No-Signaling and a Near-Identity Binary Channel Criterion

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Abstract

As a motivation, a scenario is considered in which a Weinberg-type nonlinear extension may allow violations of the no-signaling constraint, making entanglement a potential resource for operational signaling. A minimal binary model is introduced: in each run, the sender selects a binary input bit and the receiver locally records a binary output bit. Signaling is defined operationally as a dependence of the local output statistics on the remote input and is summarized by a single channel parameter estimable from data. An estimator and a robust confidence interval are constructed to test the absence of signaling, and transmission reliability is quantified via the minimum decision error. Finally, a conservative criterion is proposed, based on an upper bound on the error and a threshold fixed *a priori*, to quantify a near-identity channel regime, together with minimal reporting requirements to rule out artifacts and classical leakage.

Keywords: no-signaling; operational signaling; entanglement; nonlinear quantum mechanics; binary channel

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1. Introduction

In standard quantum mechanics, entangled correlations do not implement a controllable communication channel between spatially separated regions [1–3]. The local statistics accessible to an observer are independent of measurement choices or control actions performed remotely [4,5]. This is the no-signaling constraint.

As a motivation, it is recalled that in nonlinear extensions of the type proposed by Weinberg this constraint could, in principle, be violated [6,7]. In such a scenario, entanglement could become a resource for operational signaling [8,9].

A minimal and fully operational model is introduced. In each experimental run, the sender S selects a binary input $W \in \{0,1\}$ and the receiver R locally records a binary output $B \in \{0,1\}$. In what follows, $P(\cdot)$ denotes a probability and $P(X = x \mid Y = y)$ denotes the conditional probability that the random variable X takes the value x given that Y takes the value y. Operational signaling is present if the local distribution of the output depends on the remote choice of the input; in particular, if

$$P(B = 1 \mid W = 0) \neq P(B = 1 \mid W = 1) \tag{1}$$

The channel strength is summarized by a single parameter σ_{SR},

$$\sigma_{SR} = P(B = 1 \mid W = 1) - P(B = 1 \mid W = 0) \tag{2}$$

which is zero in the absence of any dependence of the output on the input and nonzero when such a dependence is observable.

The aim is not only to detect operational signaling, but also to characterize a regime in which the output provides a reliable estimate of the input. To this end, the transmission error probability ε is defined as the minimum error obtained by choosing the more favorable decoding between the two elementary binary maps:

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$$\varepsilon := 1 - max\{P(B = W), \quad P(B \neq W)\} \tag{3}$$

By construction, $0 \leq \varepsilon \leq 1/2$. The near-identity channel condition is formalized as

$$B \approx W \Leftrightarrow \varepsilon < \varepsilon^* \tag{4}$$

where ε^* is an experimental threshold fixed a priori. In the following, the minimal model assumptions are specified, an estimator for σ_{SR} is constructed, and a conservative quantitative criterion is defined to justify $B \approx W$.

2. Definitions and Model Assumptions

Any possible violation of the no-signaling constraint is treated exclusively in terms of observable quantities. Operationally, the input W identifies the choice between two controlled procedures applied by the sender to the same upstream prepared state; any signaling effect manifests itself as a difference between the conditional distributions $P(B \mid W = 0)$ and $P(B \mid W = 1)$. The presence of operational signaling is defined by condition (1).

The channel strength is parameterized by σ_{SR} in (2). By definition, $\sigma_{SR} \in [-1,1]$; the sign indicates which value of W increases the probability of observing $B = 1$. In a binary channel, the entire dependence of B on W is captured by the two conditional probabilities p_0 and p_1:

$$P(B = 1 \mid W = 0) := p_0, \quad P(B = 1 \mid W = 1) := p_1 \tag{5}$$

It follows that $\sigma_{SR} = p_1 - p_0$, consistently with (2). A different output-labeling convention $(B \mapsto 1 - B)$ flips the sign of σ_{SR} without changing the channel reliability; for this reason, the relevant quality measure depends on $|\sigma_{SR}|$.

To relate σ_{SR} to the near-identity channel notion, no symmetry assumption is required. Assuming balanced inputs $P(W = 0) = P(W = 1) = 1/2$, the two elementary binary decodings $\widehat{W} = B$ and $\widehat{W} = 1 - B$ are considered. In the first case, the output is interpreted directly as an estimate of the input; the average decoding error $P(\widehat{W} \neq W)$ is:

$$P(\widehat{W} \neq W) = \frac{1 - \sigma_{SR}}{2} \tag{6}$$

In the second case, the opposite convention is adopted by interpreting the complemented output as an estimate of the input; the corresponding average decoding error $P(\widehat{W} \neq W)$ is:

$$P(\widehat{W} \neq W) = \frac{1 + \sigma_{SR}}{2} \tag{7}$$

Therefore, by selecting the more favorable decoding, the minimum error ε is:

$$\varepsilon = \frac{1 - |\sigma_{SR}|}{2} \tag{8}$$

In particular, $|\sigma_{SR}| = 0$ corresponds to $\varepsilon = 1/2$ and $|\sigma_{SR}| = 1$ corresponds to $\varepsilon = 0$. The condition $B \approx W$ is thus reduced to the requirement $\varepsilon < \varepsilon^*$

3. Estimation of σ_{SR} and a Quantitative Criterion for $B \approx W$

Consider N runs described by the sequence $\{(W_k, B_k)\}_{k=1}^{N}$. The input W is assumed to be controlled by the sender and chosen independently across runs (ideally with equal probabilities), and the output B is assumed to be recorded locally by the receiver.

The data are separated according to the value of W by introducing the sample sizes n_1 and n_0:

$$n_1 = \#\{k : W_k = 1\}, \quad n_0 = \#\{k : W_k = 0\} \tag{9}$$

where $\#\{\cdot\}$ denotes set cardinality, and the counts k_1 and k_0 of outputs equal to 1:

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$$k_1 = \#\{k : W_k = 1,\ B_k = 1\},\quad k_0 = \#\{k : W_k = 0,\ B_k = 1\} \tag{10}$$

The natural estimates of the conditional probabilities are the sample proportions $\hat{p}_1$ and $\hat{p}_0$:

$$\hat{p}_1 = \frac{k_1}{n_1},\quad \hat{p}_0 = \frac{k_0}{n_0} \tag{11}$$

which estimate $P(B = 1 \mid W = 1)$ and $P(B = 1 \mid W = 0)$ respectively. The direct estimator of the channel parameter is therefore $\hat{\sigma}_{SR}$:

$$\hat{\sigma}_{SR} = \hat{p}_1 - \hat{p}_0 \tag{12}$$

For inference on σ_{SR}, a confidence interval more robust than the standard Gaussian form is adopted via the Agresti–Caffo correction [10]. The corrected counts and sample sizes $\tilde{k}_1$, $\tilde{n}_1$, $\tilde{k}_0$, $\tilde{n}_0$ are defined as:

$$\tilde{k}_1 = k_1 + 1,\ \ \tilde{n}_1 = n_1 + 2,\ \ \tilde{k}_0 = k_0 + 1,\ \ \tilde{n}_0 = n_0 + 2 \tag{13}$$

and the corresponding corrected proportions $\tilde{p}_1$ and $\tilde{p}_0$ are:

$$\tilde{p}_1 = \frac{\tilde{k}_1}{\tilde{n}_1},\quad \tilde{p}_0 = \frac{\tilde{k}_0}{\tilde{n}_0} \tag{14}$$

The corrected estimate $\tilde{\sigma}_{SR}$ and its standard error $SE(\tilde{\sigma}_{SR})$ are then defined by:

$$\tilde{\sigma}_{SR} = \tilde{p}_1 - \tilde{p}_0,\quad SE(\tilde{\sigma}_{SR}) = \sqrt{\frac{\tilde{p}_1(1-\tilde{p}_1)}{\tilde{n}_1} + \frac{\tilde{p}_0(1-\tilde{p}_0)}{\tilde{n}_0}} \tag{15}$$

Fixing a level $\alpha \in (0,1)$, a confidence interval $[L, U]$ at level $1-\alpha$ is given by:

$$[L, U] = \tilde{\sigma}_{SR} \pm z_{1-\alpha/2} SE(\tilde{\sigma}_{SR}) \tag{16}$$

To justify $B \approx W$ conservatively, an upper bound ε_{UB} on ε is constructed. From the interval $[L, U]$, a lower bound $|\sigma_{SR}|_{LB}$ on $|\sigma_{SR}|$ is obtained by defining:

$$|\sigma_{SR}|_{LB} = \begin{cases} 0, & if\ \ L \le 0 \le U \\ \min\{|L|, |U|\}, & if\ LU > 0 \end{cases} \tag{17}$$

and, using (8), the corresponding coherent upper bound ε_{UB} is:

$$\varepsilon_{UB} = \frac{1 - |\sigma_{SR}|_{LB}}{2} \tag{18}$$

The condition $B \approx W$ is taken to hold whenever

$$\varepsilon_{UB} < \varepsilon^* \tag{18}$$

By construction, ε_{UB} is a conservative upper bound on ε with confidence level at least $1-\alpha$.

4. Minimal Experimental Requirements and Reporting Criteria

The experimental evidence concerns two aspects: estimating the channel parameter σ_{SR} reliably via the point estimate $\tilde{\sigma}_{SR}$ and the confidence interval $[L, U]$, and excluding artifacts that could induce a spurious dependence between B and W. Within the adopted operational model, transmission quality is summarized by the minimum error ε via (8), and the target condition $B \approx W$ is translated into the conservative criterion.

Minimal and sufficient reporting consists of providing:

- the point estimate $\tilde{\sigma}_{SR}$ in (15);
- the confidence interval $[L, U]$ in (16) at level $1-\alpha$;
- the lower bound $|\sigma_{SR}|_{LB}$ in (17);
- the upper bound ε_{UB} in (18);
- the a priori values of α and ε^*.

The condition $B \approx W$ is justified when $\varepsilon_{UB} < \varepsilon^*$, as in (18). To rule out the possibility that a nonzero point estimate $\tilde{\sigma}_{SR}$ arises from artifacts, the following operational constraints should be required and documented:

1. Input independence. The generation of the input W should be independent across runs, and the dataset should be balanced, with comparable n_0 and n_1.
2. Acquisition invariance with respect to W. The receiver's acquisition chain should be defined without dependence on W. Triggering, gating, time windows, and validation criteria should be identical for $W = 0$ and $W = 1$. Acceptance and rejection rates conditioned on W should also be reported, and the absence of dependence should be verified.
3. Exclusion of classical leakage. Classical information pathways carrying W to R should be excluded, including wiring, synchronization or shared clocks, electromagnetic side channels, and software dependencies. Any such local dependence could produce $\sigma_{SR} \neq 0$ without implying the channel in the sense of the model.
4. Internal permutation control. By relabeling the input W through a random permutation, the same analysis pipeline should return an estimate compatible with $\sigma_{SR} = 0$ within uncertainties.

With these reporting and control elements, the final statement becomes quantitative and verifiable: $B \approx W$ in the sense that $\varepsilon_{UB} < \varepsilon^*$.

5. Conclusions

A binary operational model has been formulated in which a sender S selects an input $W \in \{0,1\}$ and a receiver R locally records an output $B \in \{0,1\}$. Operational signaling is summarized by a single channel parameter σ_{SR}, estimated from data via the point estimate $\tilde{\sigma}_{SR}$, and transmission quality is quantified by the minimum decision error ε, defined independently of the output-labeling convention.

The near-identity channel condition $B \approx W$ is quantified by fixing a threshold ε^* a priori and adopting a conservative criterion based on an experimental upper bound ε_{UB} on the error. Operationally, the experimental claim reduces to a falsifiable procedure: estimate the point estimate $\tilde{\sigma}_{SR}$ and the confidence interval $[L, U]$, derive an upper bound ε_{UB}, and verify whether $\varepsilon_{UB} < \varepsilon^*$, a sufficient condition to justify $B \approx W$ in the adopted sense.

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