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Holographic Bound and the Quantum Communications

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Abstract: In this study, the existence of a quantum constraint on the communication process between quantum systems is reviewed. This constraint is in the framework of holographic principle. It is shown that there is an interesting relation between the holographic bound and the maximum flux of quantum information.

Key words: Quantum constraint, holographic principle, quantum information, generalized uncertainty principle, channel capacity, time-energy uncertainty principle

INTRODUCTION

Quantum coherence and quantum communication are the subject of much interesting works (Tittle and Weihs, 2001; Rowe *et al.*, 2001; Schmidt-Kaler *et al.*, 2003; Leibfried *et al.*, 2003; Mandel *et al.*, 2003; Julsgaard *et al.*, 2001). An important subject in quantum information processing is existence of limits on the quantum coherence. This limit may be due to spontaneous symmetry breaking (Van Wezel *et al.*, 2005). In fact, the quantum communication is the art of transferring quantum states (Tittle and Weihs, 2001) or quantum bits of information. In this letter, we obtain a quantum constraint on a communication process between the quantum systems. Singer (1961) gave two derivations of the quantum channel capacity for noiseless channels. One derivation was based on the time-energy uncertainty principle and the second approach, however, was criticized by others (Bekenstein, 1981; Landauer, 1982) combined the classical Shannon capacity approach with the quantum noise approach. Neither gave the correct coefficient in the quantum channel capacity but both gave the correct dependence $I_{max}\propto(p/\hbar)^{1/2}$. Stern (1960) and Marko (1965) had a similar measure of success by other approaches. The thermodynamics derivation of quantum capacity is considered by Lebedev and Levitin (1963) and further described by Bekenstein and Schiffer (1990) in details. Pendry (1983) studied the channel and the carrying field and the related description of signals, unlike Shannon, was quantum one. Each possible signal is represented by a particular quantum state of the field. A case in point is provided by the bundle of electromagnetic channels which an astronomer acquires the information about a supernova explosion in a distant galaxy. However the transmitting channel is affected by noise that limits the receiver's ability to recover the encoded information. Because the noise has introduced a further measure of uncertainty the received signal is associated with larger entropy than the transmitted one. However, as proved by Shannon, elimination of errors upon reception is guaranteed only if the information is not transmitted too fast. In fact, every physical channel is characterized by a capacity which represents the maximum rate (in bites sec^{-1}) at which the information can be transmitted through it with negligible probability of errors. Note that the entropy at the receiver is maximized when the total received signal was itself Gaussian. In this letter we show that a consistent description of information transition rate may be given in terms of holographic principle. It is shown that the holographic bound can be interpreted as a bound on the transition of information between quantum systems. In continue an interesting relation was found between the holographic bound and the maximum of the information flux.

HOLOGRAPHIC PRINCIPLE AND CHANNEL CAPACITY

Consider a 3-D region with size L, volume $V\sim L^3$ and energy E (we use the natural units $\hbar = k_B = 1$). Based on the uncertainty principle, the minimum energy of a particle localized inside the region will be $E_{min}(L) = 1/L$ (This relation is obtained from $E\approx c\Delta p$ and the Heisenberg uncertainty principle) this is a quantum energy of the region. The maximum number of particles inside the region could be:

$$N_{max} \approx \frac{E}{E_{min}(L)} \approx EL \quad (1)$$

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and the Boltzmann entropy of the system is $S = \log\Omega$ (N) where the number of microstates is given by Ω (N) = 2^N (Note that for a simple system in which each degree of freedom has just two states and no degeneration of the levels). If the number of particles is bounded, we obtain an upper bound on the entropy as:

$$S_{max} < \beta EL = \beta N_{max} \tag{2}$$

where, β is a constant. The uncertainty in the position of a particle during the interacting with a photon (that radiated to localize it) is given by $\Delta x \Delta p \approx 1$. This relation doesn't consider the gravitational interaction between the particle and photon. Note that in the low energy limit, the gravitational interaction between two particles is negligible but at high energy regime this interaction is more and more important. The gravitational interaction between a particle (electron) and a photon is calculated in details by Adler and Santiago (1999), Farmany and Dehghani (2010), Farmany (2010), Farmany *et al.* (2007, 2008), Farmany (2011a, b) and Farmany *et al.* (2011). This derivation corresponds to an uncertainty in Δx inside the region of size L. the results show that due to the gravitational interaction, the uncertainty in localization of a particle is given by $\Delta x \approx G\Delta p/c^3$. Combining the gravitational and quantum uncertainty we obtain, $\Delta x \approx 1/\Delta p + G\Delta p/c^3$. Defining:

$$l_{planck} = \sqrt{G/c^3}$$

we obtains the generalized uncertainty principle:

$$\Delta x \geq \frac{1}{\Delta p} + l^2_{planck}\Delta p \tag{3}$$

Our problem is related to obtain the maximum entropy of a bounded region of space. This bound acts as a holographic bound (Hooft, 2000; Susskind *et al.*, 1993; Susskind, 1995; Bousso, 2002; Gell-Mann and Hartle, 1995; Hartle, 2004; Maldacena, 2003; Ivanov and Volovich, 2001).

Consider particles within a region with size L and minimum energy E_{min} (L)$\approx c\Delta p$. Starting from (3) one obtains:

$$E^2_{min}(L) - L^{-1}E_{min}(L) + 1 \leq 0 \tag{4}$$

Solving (4) we obtain the minimum energy as:

$$E_{min}(L) \approx L^{-1}[\frac{1}{2} - \frac{1}{2}\sqrt{1-(4/L)^2}] \tag{5}$$

Inserting Eq. 5 into Eq. 1 we obtains the maximum number of particles within the region of size L and energy E:

$$N_{max} = \frac{2EL}{1-\sqrt{1-(4/L)^2}} \tag{6}$$

Since the number of microstates is $2^{N_{max}}$ and the maximum entropy is:

$$S_{max} = \frac{2\beta EL}{1-\sqrt{1-(4/L)^2}} \tag{7}$$

The maximum information of a signal may be related to energy E and time duration τ. Our calculations are related to the channels which transmit the massive quanta. In order to maximize the information flux, we focus on the broad band channels and exclude any frequency cut-off and its associated length:

$$I_{max} = f(E, \tau) \tag{8}$$

Because I_{max} is dimensionless, so f (E, τ) may be a dimensionless combination of E and τ. So we can write:

$$I_{max} \propto (E\tau) \tag{9}$$

One can set a holographic bound on the channel capacity depending only on the maximum signal entropy. The frequencies that can appear are bounded to $1/\tau$ and contain a noise which may be calculated by employing the energy-time uncertainty relation for a signal with duration time τ.

E_{min} (L) is the lowest quantum energy level and ΔE is the smallest energy separation between levels beneath E (L). The total number of occupied levels is obtained from Eq. 6 and the total number of configurations is bounded from above by the number of configurations of a system composed of $M_{max} = E/\Delta E$, where M_{max} is the number of Bosons distributed among N_{max}. Substituting the holographic bound on E_{min} and N_{max} equating S_{max} with the peak information (signal) and covering to bits we obtains:

$$I_{max} \leq \frac{N_{max}}{E_{min}(L)} \tag{10}$$

This argument is only valid for large N and makes use of the popular version of the holographic bound for communication and information theory.

CONCLUSION

It is interesting that a holographic bound can be applied to the channel capacity depending on the maximum signal entropy. The frequencies that can appear are bounded to 1/τ and contain a noise which may be calculated by employing the energy-time uncertainty relation. It is shown that the holographic bound can be interpreted as a bound on the transition of information between quantum systems.

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