Final proof for optimal encoding strategies in optical communication

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The massive transfer of data over the Internet that is vital to today's economy in our information society would not be possible without the crucial role played by fibre optics communication. Every time a node of the Internet sends information, it encodes a sequence of digital bits composing the message into light pulses. These light pulses are later sent through an optical fibre to a receiving node that converts the light signal back to the original sequence of bits. The increase demand for higher data transfer raises the natural question on what are the fundamental physical limits to the information transmission rate over optical links. Raul García-Patrón, former member of the Theory Division of Professor Ignacio Cirac at the Max Planck Institute of Quantum Optics, with collaborators from Pisa, Brussels and Moscow, has recently answered this question, concluding a research program that started during his Humboldt postdoctoral fellowship at the MPQ between the years 2011 and 2013.

It has been known since the pioneering work of Albert Einstein that light is composed at its smallest scale by quantum particles called photons. Therefore, a definitive answer to the question on the ultimate limits to optical communication needs to consider the quantum nature of light. It was already at the beginning of the 1960s, after the development of the laser together with the development of the modern quantum theory of light, when the question on the fundamental physical limits to the information transmission rate over optical links was raised. But it was only a few decades later, at the birth of quantum communication theory at the end of the 1990s, that the right tools necessary to answer this question were developed by the pioneering work of Professor Alexander Holevo (co-author of this manuscript). Subsequent work conjectured that the optimal strategy to send information over optical communication lines does not need the generation of highly complex quantum states, but simple light pulses generated by currently existing lasers are sufficient to reach the optimal communication rates. But no definitive answer had been given since then.

In a previous work in 2012 (*Phys. Rev. Lett.* 108, 110505, 2012), Raul García-Patrón (working then at the Theory Division at MPQ), in collaboration with Carlos Navarrete-Benlloch (current member of the Theory Division) and other scientists from the Universite Libre de Bruxelles and Massachusetts Institute of Technology, showed that any realistic optical communication channel can be modelled by a concatenation of an ideal attenuation channel followed by an ideal process of amplification. Therefore, the former conjecture on the optimal strategy to encode information could be reduced to a basic question: what is the minimum disorder, or entropy, that is added to the input signal by one of the most studied quantum optical processes, namely optical parametric amplification? "Entropy is a measure of disorder. Minimum output entropy of the channel measures how much the channel distorts the input state that you initially sent through the line", Dr García-Patrón explains. "The highest achievable bit rate is given by a function that is optimized by minimizing the output entropy of the channel. Intuitively it means you want to minimize the distortion the channel produces to your input signal." Now the team of scientists were able to prove that a Gaussian encoding achieves minimum out-put entropy and hence provides the ultimate capacity of an optical communication channel. Gaussian states are the most natural states of light. Gaussian channels that preserve the "Gaussianity" of the state are the most natural models of optical communication links, for example fibres or amplifiers. Following the roadmap that was suggested in its previous work (the Physical Review Letters mentioned above) Dr.

Garcia-Patron and collaborators successfully solved this longstanding open problem exploiting some known properties of the amplifier channels in a novel way.

The solution may have implications in other fields of physics, as many physical systems are mathematically modelled by bosonic Gaussian states and channels, for example, thermodynamical processes of bosonic systems, the theory of entanglement in Hawking radiation in black-holes, or superconducting systems. However, a few questions remain that wait to be answered. "We know that very simple states achieve an optimal encoding. But we do not know if the same holds for the decoding of the information", says García-Patrón. "Our result just gives a proof of existence: we know there is a detector achieving our rate, but further research is needed to find a realistic optimal decoding that could be implemented. As far as future applications are concerned, a simple efficient decoding could be useful e.g. in regimes where the signals are extremely weak at the reception, as in earth to deep-space communication."

More information: V. Giovannetti, R. García-Patrón, N. J. Cerf and A. S. Holevo "Ultimate classical communication rates of quantum optical channels by solving the Gaussian minimum-entropy conjecture." *Nature Photonics*, Advance Online Publication, 21 September 2014

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