Exploring the quantum limits of optical communication

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Quantum physics offers new ways to enhance the performance of optical-communication systems using phenomena specific to the microscopic world.

The quantum nature of light imposes limitations on the ultimate performance of optical systems. For example, a light pulse must contain at least one photon for reliable detection by a receiver. This assumes that no losses or dark counts (false alarms when no photon is received) occur in the detection process. Such limitations raise nontrivial questions about the capacity of optical-communication systems, even in the ideal situation when all sources of excess technical noise have been suppressed. These and similar questions initiated the development of the theory of quantum-communication channels.

In practice, one needs to take into account physical effects introduced by the transmission medium. These include attenuation of the light amplitude or random birefringence in optical fibers. Full quantum analysis of imperfect communication channels leads to intriguing results, especially if the channel noise exhibits correlations.

Our research group has demonstrated how quantum phenomena may enhance optical communication. Suppose that the communication link is an optical fiber with fluctuating birefringence and that our task is to encode information into the polarization degree of freedom of single photons, using as few of them as possible. In that context, a single photon is useless, because it would emerge in a completely random polarization state. However, as the birefringence varies slowly, two photons sent one right after another will experience a virtually identical, highly correlated polarization transformation.

This suggests that at the channel output, the polarization of one photon could serve as a reference for the other. However, a single photon cannot provide complete data on the polarization transformation that occurred in the channel, because quantum physics only allows discrimination between orthogonal polarization states of a single photon. We can tell for sure whether it is horizontally or vertically polarized, but there is no way to distinguish with certainty horizontal from circular polarization. Nevertheless, we could try to encode a bit of information into two photons prepared in either identical or orthogonal polarizations. However, a detailed calculation shows that after transmission through a birefringent fiber, these two possibilities cannot be discriminated unambiguously. The amount of information that can be encoded this way is slightly more than 0.32 bit. This is the best result possible to date using two photons with well-defined polarizations.

However, this is not the last word in quantum physics. It is possible to prepare a pair of photons in a special joint polarization state (the singlet state), which has a total electron spin of zero. If we look at only one photon in such a pair, its polarization seems to be completely random. By contrast, the polarization state of both photons is defined as precisely as possible in quantum theory: when measuring the polarizations of both photons simultaneously, they turn out to be orthogonal. This is

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true no matter whether we check them on a horizontal/vertical, left/right-circular, or any other basis. Such perfect anticorrelations are not possible in classical physics, but they are a signature of a very peculiar quantum feature known as entanglement, in which the quantum states of objects are linked so that one object cannot be described adequately without mentioning the other.

The crucial feature of the singlet state in our communication scheme is that it remains completely unscathed when the photon pair is sent through a birefringent fiber. This is because orthogonal polarizations at the input are transformed into orthogonal (although generally different) polarizations at the output. This uniquely identifies the singlet state, which can be distinguished unambiguously from two photons prepared in identical polarizations through a measurement based on two-photon interference. This allows us to faithfully encode one bit of information by preparing two photons in either the singlet state or identical polarizations, which is more than a three-fold improvement. Figure 1 shows the nonlinear crystals we used to generate entangled states.

Correlated birefringence is only one example of a deleterious mechanism that might occur in an optical channel. Another common phenomenon is attenuation, which is important in communications and which may affect the precision of interferometric measurements.

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Konrad Banaszek received his PhD from the University of Warsaw, Poland, in 2000. After postdoctoral appointments at the University of Rochester, the University of Oxford, and St. John’s College, Oxford, he joined the faculty of the Nicolaus Copernicus University in Toruń, Poland. His research focuses on quantum optics and quantum-information processing and communication.

References