measurement outcomes are not precisely defined. Instead of a set of orthonormal projector operators, we require a more general set of operators that describe the measurement outcomes and are chosen to satisfy the normalization constraints. This set — called the positive-operator-valued measure (POVM) — includes the von Neumann orthonormal operators. For a given quantum state of light impinging on a detector, the Born rule expressed in terms of the POVM can give the correct probability of any possible outcome.

Although the problem of fully characterizing a detector by reconstructing its POVM with quantum detector tomography was suggested several years ago[2,3], researchers have only recently begun to conduct the first experiments[4,5]. However, in the few cases where experimental detector tomography has been successfully performed, the studies have assessed only the detector's ability to count the discrete number of photons in the incoming light signal.

Consider the classical case of detecting a light beam with a photodiode. The only information that can be extracted from the measurement is the intensity distribution in the beam. Determining the phase structure of the field requires an interferometric scheme that mixes the original beam with a reference field (the local oscillator) at a beamsplitter. Homodyne detectors employ a similar scheme in the quantum domain to reconstruct the complete characteristics of a quantum light state (not just its photon-number distribution probability).

The first full tomography of a homodyne detection set-up, reported by Zhang *et al.*[1], is therefore a huge advancement over previous results. The technique allows the complete characterization of one of the most powerful and widely adopted detectors in the quantum realm, where phase-sensitive measurements are crucial, both for fundamental studies of quantum physics[6] and for future communication applications.

Zhang *et al.* have analysed a particular type of homodyne detector in which one of the outputs of the mixing beam splitter is detected by either an on/off single-photon detector or a photon-number-resolving photodetector. This hybrid optical detector can therefore operate in the ambiguous region between discrete (photon number) and continuous (homodyne) detection, as the detector's response can be changed from particle- to wave-like behaviour by tuning the strength of the local oscillator. The detector operates with single-photon resolution in the limiting case of zero local oscillator intensity, thus providing information on the energy distribution of the impinging light. However, when the intensity of the local oscillator is non-zero, the scheme provides phase information by acting as a phase-sensitive detector.

A complete analysis of this dual detection scheme requires the corresponding POVMs to be described in a large Hilbert space, where the diagonal elements of their matrix representations illustrate the photon-number resolution nature of the detector and the off-diagonal elements depict the phase sensitivity acquired by the interferometric nature of the measurement. Reconstructing such a huge number of matrix elements from experimental data is a formidable task that is beyond conventional approaches. In this regard, another important achievement reported by Zhang *et al.* is the development of a new analysis procedure that reduces the computational complexity of the tomographic reconstruction problem and thus allows detector POVMs for up to a million matrix elements to be determined.

By including the measurement apparatus as part of the analysis, detector tomography could be used to complete the entire quantum description of any possible experiment. Zhang *et al.* have taken an important step forwards in this direction by enlarging the class of testable detectors and providing the tools to make this task experimentally and computationally feasible. In addition, the full quantum characterization of a detector in terms of both photon-number resolution and phase sensitivity opens up exciting opportunities for new quantum state engineering and detection techniques in quantum information processing. ❐

Alessandro Zavatta and Marco Bellini are at the Istituto Nazionale di Ottica (INO-CNR) Largo E. Fermi 6, 50125 Firenze, Italy, LENS and Dipartimento di Fisica, Università di Firenze, Italy. e-mail: alessandro.zavatta@ino.it

References

1. Zhang, L. *et al. Nature Photon.* **6,** 364–368 (2012).
2. Luis, A. & Sánchez-Soto, L. L. *Phys. Rev. Lett.* **83,** 3573–3576 (1999).
3. D'Ariano, G. M., Maccone, L. & Lo Presti, P. *Phys. Rev. Lett.* **93,** 250407 (2004).
4. Lundeen, J. S. *et al. Nature Phys.* **5,** 27–30 (2009).
5. D'Auria, V., Lee, N., Amri, T., Fabre, C. & Laurat, J. *Phys. Rev. Lett.* **107,** 050504 (2011).
6. Parigi, V., Zavatta, A., Kim, M. S. & Bellini, M. *Science* **317,** 1890–1893 (2007).

QUANTUM COMMUNICATION

Approaching the quantum limit

Interrogation schemes based on quantum physics look set to push the data-handling capabilities of optical communication channels to new levels of performance.

Konrad Banaszek

Optical communication, thanks to its high efficiency and reliability, has become the primary network infrastructure for supporting the communication needs of today's society. Increasing data transmission rates provided by successive generations of optical communication systems are now enabling applications such as cloud computing and high-definition television broadcasts. These successes make one wonder about the ultimate transmission rates that can be achieved over an optical channel. The achievable rate depends on factors such as the transmitted power of the light used to encode information, the usable spectral bandwidth of the channel and, ultimately, the noise present in the receivers decoding the signal[1]. From a fundamental perspective, the receiver noise must be at a certain above-zero level that is related to the physical phenomenon of quantum fluctuations. This noise prevents the state of the incoming light from being identified with perfect accuracy.

Quantum-limited performance is typically not reached by conventional optical receivers that employ standard strategies for signal detection. However, in this issue of *Nature Photonics*[2], Chen *et al.* report the enhanced readout of optical signals beyond what can be achieved through the traditional technique of direct detection. Specifically, they consider the case of pulse-position-modulation encoding, in which information is transmitted as the location of a light pulse in a number of otherwise empty

© 2012 Macmillan Publishers Limited. All rights reserved.

time bins. The task of decoding consists of finding out which of the time bins is not empty — akin to a game in which an object, say a gemstone, is contained within one of a number of boxes. We are allowed to look once into each box, but because the gemstone is so tiny, there is a non-zero chance that it may be overlooked. If this happens, we cannot say anything about the location of the gemstone. Chen *et al.* implement a new strategy for examining the boxes in which the procedure chosen for a subsequent box depends conditionally on what we have learned from previous boxes. They convincingly demonstrate that this techinque can bring us closer to the ultimate quantum limit of performance.

Before describing their strategy in more detail, let us first consider why the problem of verifying the contents of a single box is so non-trivial. Suppose that a logical '1' is represented by a light pulse with a non-zero amplitude, whereas a logical '0' is transmitted as an empty time bin. This encoding approach is known as on–off keying. The most straightforward decoding strategy is to use direct detection, in which the detector simply measures the power of the light pulses. However, even an ideal detector with unit quantum efficiency may not 'click' for very weak pulses; that is, we may miss the presence of a gemstone in the box, leading to errors in the communication channel (Fig. 1a). The probability of an error decreases exponentially with the total pulse energy. Classical information theory provides a well-defined quantity — the channel capacity — that tells us what the maximum transmission rate is for a given relation between input symbols and output results. Figure 1b depicts this quantity as a function of pulse energy for direct detection. When the energy tends towards zero, the capacity vanishes because there is no longer any way to distinguish between the input symbols, whereas for a large pulse amplitude, discrimination is nearly perfect and the channel capacity approaches one bit per channel.

Imperfect distinguishability has a fundamentally quantum-mechanical origin. The two preparations used to encode information — a pulse and an empty time bin — correspond to quantum states of light that are mutually non-orthogonal. This non-orthogonality means that perfect discrimination is not possible, even in principle. According to quantum mechanics, we must think about the pulse amplitude as a fluctuating quantity, even if it has a zero value, with the minimum noise level imposed by the Heisenberg uncertainty relation. Given this limitation, let us approach the problem from the another

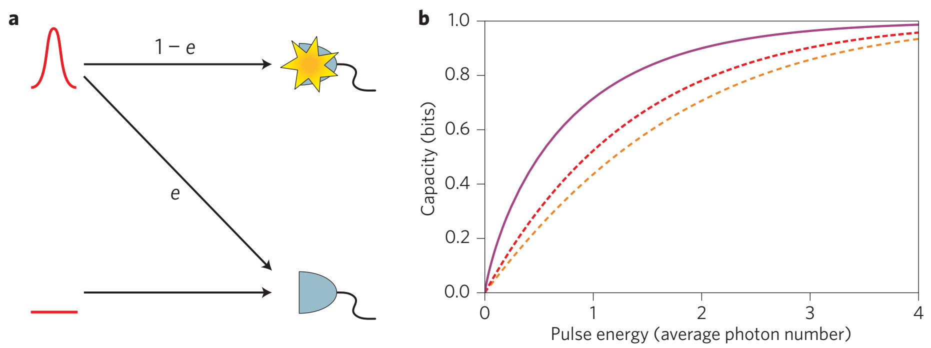

Figure 1 | Detection of binary information encoded as an on/off pulse. **a**, Direct detection mistakes a light pulse for an empty bin with an error rate of *e*. **b**, The capacity of different detection approaches. The capacity of direct detection (orange dashed line) is below the Helstrom bound (red dashed line). Collective detection included in the Holevo bound (solid purple line) provides a significant improvement in performance.

direction: what is the fundamental quantum bound on discriminating two states? The solution to this problem, presented by Helstrom in the 1970s[3], implies that direct detection is suboptimal, as seen in Fig. 1b. However, the practical realization of a quantum measurement capable of saturating the Helstrom bound is highly non-trivial. A feedback-based scheme employing photon counting and coherent displacements was demonstrated only recently in a proof-of-principle experiment[4].

Fortunately, quantum mechanics teaches us to consider very carefully what information about the physical system is of interest, and to devise the detection strategy accordingly. In particular, it turns out that more information can be extracted if the measurement is performed collectively on several elementary systems — in our case individual time bins. This can happen even if the states chosen for consecutive transmissions are selected independently. By including the possibility of collective measurements[5], Holevo derived a channel capacity bound that further improves the transfer rate (Fig. 1b). However, researchers have yet to demonstrate a collective receiver that approaches the Holevo limit for on–off keying.

Given that the discrimination between a light pulse and an empty time bin reveals so many subtleties, exploring the options offered by quantum mechanics should also benefit more complex coding schemes. In the case of pulse-position-modulation encoding, the problem with direct detection is that missing the pulse results in an inconclusive output. Chen *et al.* go beyond this limitation by introducing two ingredients. The first is a nulling measurement that can be applied to a single time bin, thereby effectively swapping the roles of the pulse and empty bin shown in Fig. 1a. This enables an empty bin to be identified unambiguously, although only in a fraction of all cases. The second ingredient is the ability to select the measurement applied to a subsequent pulse based on the history of past events. This strategy starts with applying the nulling measurement to the first pulse. If we learn that the pulse was definitely not there, we continue applying the nulling measurement to subsequent bins until we obtain the response that could have been generated by a pulse. Once this occurs, we test the hypothesis that the pulse was indeed present in the 'suspicious' bin by switching to direct detection for the remaining bins. This hypothesis is corroborated if direct detection yields no clicks at all; otherwise an occurrence of a click unambiguously identifies the location of the pulse in one of the directly detected bins. Implementing this strategy enabled Chen *et al.* to reduce the error rate by up to 40%, compared with direct detection under the same experimental conditions.

Naturally, the two ingredients necessary for realizing conditional pulse nulling come with a price tag. First, pulse nulling relies on destructive interference between the incoming signal and a train of local auxiliary pulses with a well-defined relative phase. Fortunately, access to a phase-locked optical reference field is also required by many of the coherent detection schemes that are currently being explored for increasing transmission rates in optical communication systems[6]. Second, switching from nulling to direct detection must be realized on a timescale that is shorter than the spacing between consecutive time bins. In their proof-of-principle demonstration, Chen *et al.* separated individual bins by 1 μs, which is thousands of times longer than the values typical of modern fibre-optic communication.

© 2012 Macmillan Publishers Limited. All rights reserved.

From a practical point of view, an important question is how much investment is needed to incorporate quantum-enhanced techniques into today's telecommunications systems. The cost of constructing devices capable of operating at the quantum limit must be balanced by the benefits of increased transfer rates. It would be premature to predict how quickly the development of this technology will progress. What is certain, however, is that sooner or later optical communication will approach the performance limits defined by quantum mechanics. We are already getting prepared for the ensuing challenge, while at the same time gaining fascinating insights into the physical foundations of modern information technologies. ❐

Konrad Banaszek is at the Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland.
e-mail: konrad.banaszek@fuw.edu.pl

References

1. Caves, C. M. & Drummond, P. D. *Rev. Mod. Phys.* **66,** 481–537 (1994).
2. Chen, J. *et al. Nature Photon.* **6,** 374–379 (2012).
3. Helstrom, C. W. *Quantum Detection and Estimation Theory* (Academic, 1976).
4. Cook, R. L., Martin, P. J. & Geremia, J. M. *Nature* **446,** 774–777 (2007).
5. Holevo, A. S. *Probl. Inf. Transm.* **9,** 177–183 (1973).
6. Ip, E., Lau, A. P. T., Barros, D. J. F. & Kahn, J. M. *Opt. Express* **16,** 753–791 (2008).

VIEW FROM... FRONTIERS OF PLASMONICS

The new facets of plasmonics

Quantum plasmonics, Fano resonances, surface plasmon–polariton Airy beams and plasmon-enhanced Raman spectroscopy are some of the new aspects of plasmonics that are now being explored.

Noriaki Horiuchi

Using nanostructures to control surface plasmon–polaritons (SPPs) opens up important new avenues for interdisciplinary research in the field of plasmonics. Plasmon resonance biosensors and tip-enhanced Raman spectroscopy — well-known examples of such interdisciplinary work — demonstrate one of the main advantages of SPPs: their ability to achieve electric field localization within an area smaller than the wavelength of the probe beam. However, SPPs are also endowed with a range of other properties that are yet to be fully explored in photonics research. Such new and intriguing properties were the primary focus of the Second International Conference on Frontiers of Plasmonics (FOP2), which was held on 8–12 April 2012 at Sichuan University, Chengdu, China.

Quantum plasmonics, although long a subject of interest to researchers in the field of plasmonics, has proved difficult to observe owing to surface–ligand interactions and inhomogeneity in ensemble measurements, which blur the plasmon resonance spectrum. Jennifer Dionne from Stanford University in the USA reported experimental results on the quantum plasmon resonances of ligand-free silver nanoparticles. The key success demonstrated by Dionne and co-workers was the simultaneous measurement of aberration-corrected transmission-electron microscope (TEM) imaging and monochromated scanning TEM electron energy-loss spectroscopy. She presented a direct correlation between a particle's geometry and its plasmon resonance, in which decreasing the nanoparticle diameter from 20 nm to 2 nm caused the plasmon resonance to blue-shift from 3.3 eV to 3.8 eV. However, for a particle with a diameter smaller than 10 nm, the results presented a substantial deviation from the numerical simulation, which is based on conventional SPP theory. "This deviation is due to a change in particle permittivity. The analytical quantum-mechanical model well-describes the plasmon resonant shift," Dionne explained to *Nature Photonics*.

NORIAKI HORIUCHI

More than 150 attendees from 17 countries gathered at the 2nd International Conference on Frontiers of Plasmonics.

Javier Aizpurua from the Spanish Council for Science Research presented a number of theoretical examples in which quantum plasmonics could result in a conductive contact between the two arms of a gap antenna. "The classical description, which is an abrupt change of the electron density at the surface, is no longer valid for calculating optical response of a gap antenna with subnanometre arm-separation distance. A quantum description, which involves modelling how the electrons spill out at the surface of the metal, seems more accurate," explained Aizpurua. The problem with the full quantum-mechanical description is that performing the necessary calculations for every electron involved in the optical response of a standard plasmonics system is beyond the capabilities of today's computers, he added. Aizpurua therefore proposed a new technique for calculating the quantum effect based on parametric inputs derived from simpler classical calculations, the validity of which he also examined.

Another exciting subject discussed at the conference was Fano resonances, which result from interference between excitation modes. The line shape of a nanoplasmonic resonance can be tuned by appropriate design of the nanostructures used to control the SPPs. One particularly interesting aspect of Fano resonances is their potential for line-shape narrowing, which could enable new kinds of highly sensitive optical nanobiosensors. Peter Nordlander from Rice University in the USA highlighted a number of recent applications that employ Fano resonances. Stefan Maier from Imperial College London in the UK described his group's theory of Fano interference, which provides a parameter-free description of the resonance by adapting Fano's original formalism to cover the case of a plasmonic nanocavity. According to Maier, their theory enables cavities to be designed with a desired modulation depth at the Fano resonance and provides an understanding of how such resonances arise in complex cluster systems.

© 2012 Macmillan Publishers Limited. All rights reserved.