Entanglement enhances classical communication

As a laboratory experiment shows, when Alice and Bob each have one of a pair of entangled photons, they can transmit data more accurately over a noisy channel.

Quantum entanglement, by itself, cannot be used to communicate. Measuring the state of one qubit can instantaneously change the state of its entangled partner, no matter how far away, but that change can't convey a message. Entanglement can, however, enhance the security, capacity, or accuracy of a communication channel.

In one example, researchers led by William Matthews (University of Waterloo, Canada) and Andreas Winter (University of Bristol, UK) showed last year that when two communicating parties—Alice and Bob—share pairs of entangled qubits, they can transmit more classical information in a single use of a communication channel than they otherwise could.[1] Matthews and Winter's work was theoretical. Now, Robert Prevedel, Kevin Resch, Matthews, and other Waterloo colleagues have implemented a similar protocol experimentally.[2] Without shared entanglement, a single use of their channel can transmit a single bit with a success rate of 83.3%. With shared entanglement, the researchers achieved an experimental success rate of 89.1 ± 0.2%, not far from the theoretical limit of 90.2%.

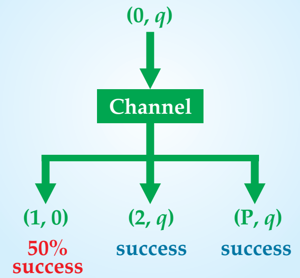

Figure 1. A classical strategy for transmitting a bit q over a noisy communication channel. The channel takes two bits as input; it outputs either the first bit, the second bit, or their parity P, each with equal probability. Inputting (0, q) gives a success probability of 5/6, or 83.3%. Several other strategies do equally well.

Scheming to communicate

A classical communication channel is one that transmits classical information; in contrast, a quantum communication channel transmits quantum states. A discrete memoryless classical channel—the type under consideration—takes one of a finite set of inputs and returns an output that depends on the input and on a conditional probability distribution, but not on any previous behavior of the channel. For example, a channel might take a bit (a 1 or 0) as input and output the same bit 90% of the time and the opposite bit 10% of the time.

The general form of an entanglement-enhanced communication scheme is as follows. Alice and Bob each possess one of a pair of entangled quantum systems. (In the new experimental work, the system is a polarized photon.) Alice makes some measurement on her system, determined by the message q she wants to communicate, and thereby changes the state of Bob's system. Her measurement outcome and the message q determine what input she enters into the communication channel. Bob receives the channel output, and he uses it to decide what measurement to make on his system. He then uses his measurement result to infer q.

Matthews, Winter, and colleagues were interested in the zero-error capacity, the maximum amount of information a channel can transmit with no chance of error. The channel they used in their example was complex, with 24 possible inputs and 18 possible outputs. The theorists found a set of five inputs with nonoverlapping output distributions, so a message q drawn from a set of five possible messages could be communicated without error. With the benefit of shared entanglement, q could be drawn from a set of six messages.

Matthews approached Resch and his group to find out if the theoretical result could be reproduced in the laboratory. But the experimentalists quickly realized that implementing Matthews's protocol would be impractical. Each entanglement-assisted use of the channel required two pairs of entangled qubits. In the experiment, the qubits would take the form of polarization-entangled photons. The experimenters found that they couldn't make the necessary joint measurements on pairs of photons with sufficient accuracy.

So Matthews devised another protocol that used a simpler channel and just one pair of entangled photons. The channel takes as input a pair of bits—(0, 0), (0, 1), (1, 0), or (1, 1)—and, with equal probability, outputs the first bit of the pair, the second bit, or their parity (sum modulo 2), along with a symbol—1, 2, or P—indicating which of those three possibilities the output represents. That is, if the input is (x, y), the output is either $(1, x)$, $(2, y)$, or $(\mathrm{P}, x \oplus y)$, where $x \oplus y$ is the parity.

The channel has no zero-error capacity, since any two of the four possible inputs have an output they can both produce. If Alice and Bob want to use the channel to communicate a message q consisting of one bit, the best they can achieve is a success rate of 5/6, or 83.3%. One of several equally good strategies is shown in figure 1. Alice inputs $(0, q)$. Two-thirds of the time, the channel outputs either the second bit $(2, q)$ or the parity $(\mathrm{P}, 0 \oplus q = q)$, and the communication is a success. One-third of the time, it outputs the first bit $(1, 0)$, and Bob learns nothing about q, so he has to guess. His guess is correct 50% of the time, for an overall success rate of 83.3%.

Entanglement enhancement

If Alice and Bob each possess one of a pair of polarization-entangled photons, they can better exploit the channel by using the scheme shown in figure 2. Alice measures her photon's polarization in a direction that depends on q: If $q = 0$, she measures at angle $\pi/4$, and if $q = 1$, she measures at angle 0. She represents her measurement result as a bit α, which equals 0 if the photon is polarized in the direction of measurement and 1 if it's polarized in the perpendicular direction. As a result of her measurement, Bob's photon is now in the same state as she just measured.

Alice inputs (q, α) into the channel. If Bob receives $(1, q)$, he needn't do anything more; the protocol is a success. Otherwise, he must make a measurement on his photon. If he receives the parity $(\mathrm{P}, q \oplus \alpha)$, he measures at angle $\pi/8$, midway between the two possible directions of Alice's measurement. With probability $\cos(\pi/8)$, or 85.3%, Bob's measurement gives the same result as Alice's, no matter which measurement Alice made. Therefore, 85.3% of the time, Bob knows both α and $q \oplus \alpha$, from which he can compute q.

If Bob receives $(2, \alpha)$, he measures at angle $3\pi/8$. If $q = 0$ and Alice measured at angle $\pi/4$, Bob has an 85.3% chance of getting the same result as Alice did. But if $q = 1$ and Alice measured at angle 0, there is an 85.3% chance that Alice's and Bob's results are different. In either case, with 85.3% probability, Bob's measurement result is equal to $q \oplus \alpha$. Once again, Bob knows both α and $q \oplus \alpha$, so he can compute q. The overall success rate of the scheme is therefore 90.2%.

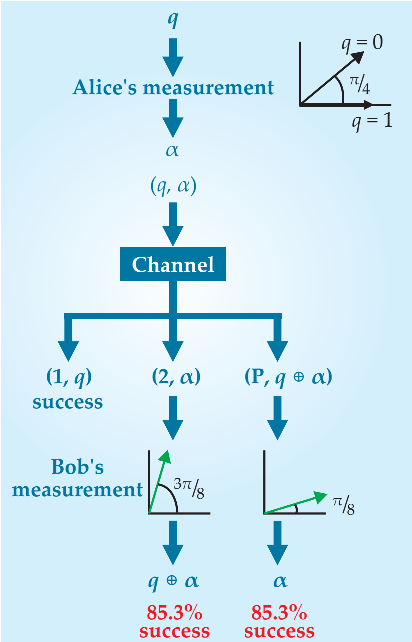

Figure 2. An entanglement-enhanced strategy for transmitting a bit q. Alice measures her photon's polarization in one of two directions, depending on q. She represents her result as a bit α and inputs (q, α) into the channel. Bob then measures his photon, the entangled partner of Alice's photon, in one of two directions, depending on the output he receives from the channel. Bob can then deduce q with an overall success probability of 90.2%.

In Resch and colleagues' experimental implementation, "Alice" and "Bob" are different parts of the same lab table. Their entangled photons, generated by a nonlinear optical process called spontaneous parametric down-conversion, are delivered to them through optical fibers, with Bob's passing through a 50-meter delay line so he doesn't receive it until he's ready to make his measurement. Alice's photon passes through a beamsplitter, which randomly determines which of two polarization analyzers it will enter and thus if the message q is 0 or 1. Rather than rotate Bob's polarization analyzer, the researchers use Pockels cells, or voltage-controlled wave plates, to rotate Bob's photon based on the electronic output of the noisy classical channel.

That setup allowed the experimenters to repeat the entanglement-enhanced communication more than 300 times a second. In 10 minutes of data collection, they measured a success rate of $89.1 \pm 0.2\%$, with the error bar derived from Poisson counting statistics. The researchers attribute the deviation from the ideal success rate of 90.2% to imperfect creation of the entangled state and corruption of Bob's photon in the delay line.

Although the experimental result is based on repeated use of the channel, the measurement represents the success probability of a single use. Better schemes exist, even without entanglement, for transmitting n bits through n uses of the channel, for n greater than 1. For example, to use the channel twice to transmit two bits x and y, Alice does better to input (x, y) twice than to input $(0, x)$, then $(0, y)$, and there are schemes for which the error rate goes to 0 as n goes to infinity. It's been shown that entanglement can't increase the maximum rate of information transfer in the limit of infinitely many uses of any classical channel.[3] But Matthews and other Waterloo theorists have found that entanglement sometimes can increase the communication rate in the limit of many channel uses if the error must be exactly zero. Says Matthews, "We've been trying to get a better understanding of what exactly shared entanglement can and can't do."

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References

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3. C. H. Bennett et al., *Phys. Rev. Lett.* **70**, 1895 (1993); C. H. Bennett et al., **83**, 3081 (1999).

Microfluidic devices streamline fluorescence experiments

Reactions orchestrated on chips the size of a penny elucidate protein folding and other complex biological processes.

Louis Sullivan had architecture in mind when he declared that "form ever follows function." Had his interest been biomolecules instead of buildings, he might have inverted the famous credo—when it comes to biological processes, a molecule's effect nearly always depends on its shape. An improper protein fold, for example, can spell the difference between a vital organism and a fatally diseased one.

Understanding biological systems,