optics & photonics focus

Pipes Unclogged: The Quantum Physics Way!

Quantum effects are often portrayed as far more fragile than classical physics effects. However, classical physics sometimes lets us down when it comes to errorless transfer of data; when this is the case, quantum physics could come to the rescue!

If tap water tastes funny, it is advisable to filter it before drinking. The same goes for communications: if data received is contaminated with errors, then these errors will have to be filtered out, and the original message reconstructed. Nevertheless, a probability remains, albeit tiny, that not all contamination will have been removed, in spite of the cleaning. In the cases where no contamination whatsoever is a must, then clean water has to be sought elsewhere, or alternative means of communication for the transmission of errorless messages looked into. Interestingly, in the case of communications, quantum physics can sometimes provide an alternative means to achieving an errorless transmission, even when classical physics cannot. This is what was recently presented by Jianxin Chen from the Universities of Guelph and Waterloo in Canada, together with Toby S. Cubitt (Universidad Complutense de Madrid), as well as Aram W. Harrow (University of Washington) and Graeme Smith (IBM TJ Watson Research Center). Once again, quantum physics defies ordinary intuition and strikes us with a fascinating phenomenon.

Water pipes and communication channels have a lot in common. In the case of the former, water is sent through a channel to a receiver at the other end; and in the case of the latter, information. Both channels are often characterized by their capacity and their loss rate. The capacity refers to the volume that can be transferred: in the case of water pipes, to the amount of water they can carry, and in the case of communication channels to the number of binary digits — *bits* in short — that can be transmitted in a given unit of time. The loss rate describes how much water is lost due to leakages or how many bits are lost due to absorption in the communication channel.

When considering communication channels in particular, the degradation of the signals also needs to be taken into account. For water pipes, this would correspond to a poorly made water pipe from which toxic chemicals wash out. Ordinarily, the water used to wash out the toxic chemicals would need to be filtered until the contamination was below harmful concentrations or regulatory limits. If, however, the contaminating chemicals were very dangerous, and our loved ones needed to drink from this water, then zero contamination would have to be ensured. Even a little bit of contamination would be 'too much' in this case! This quantity of perfectly clean water that can be transmitted through a pipe is what we could refer to as the *zero-contamination capacity*. In communication theory, the analogous quantity of information that can be transmitted with absolutely no error whatsoever is called zero-error capacity.

Figure 1: Water and information distribution. Water and information is distributed through channels. Pipes transport water, communication channels, such as fiber-optic cables, transport information. Image: wikipedia/Hephaestos.

To even further understand what Chen and co-workers have studied, consider the following situation: imagine two parallel water pipes, of such poor quality, that no water can be transmitted without contamination. Obviously, using both pipes at the same time is not going to help avoid contamination. The same holds true when you have two very bad *classical* communication channels. Using them both in parallel is not going to significantly improve the quality of the message. However, things work differently for quantum communication channels. If you were to use entangled quantum bits of information, Chen and co-workers have proved that you would still have a chance of transmitting at least some zero-error information. Intuitively speaking, this would be analogous to saying that if 'entangled water' is sent through, then at least some "uncontaminated" water would pass through the two water pipes. In other words, entanglement can unclog an information blockage in communication channels. This effect that two pipes can improve the zero-error transmission is called *super-activation*.

Entanglement [1] is one of the most intriguing features of quantum physics: imagine, for example that two coins were entangled in a way that caused them, once flipped, to land on the same side. Of course, if the coins were able to communicate, they might agree upon which side to land on. However, quantum entanglement does not involve any communication at all! In fact, the phenomenon of entanglement is so deep and so surprising, that Albert Einstein famously referred to it as "spooky action at a distance." Today, we still do not know the mechanism that leads to this effect – all we know is that it exists, that it is included in quantum theory, and that we can observe it and work with it in our experiments.

Quantum physics is often presented as more fragile than classical physics. This intuition is largely due to the apparent fragility of entanglement: imagine that one thousand coins were entangled in a way that meant they would all land on the same side. Prior to flipping, all coins would have equal probability of landing on either of the two sides, and hence still be in this quantum state of "have not yet decided which side to land on but it will be the same as all the other coins." However, it is enough to merely flip one coin to destroy all of the coins' collective quantum state completely. Before flipping the coin, all of the coins had the potential of landing on either heads or tails, but all 1000 of them would land on the same one. As soon as one of the coins has been flipped then all of them are in the same definite state of either heads or tails. Their state can now be described using classical physics and the magic of entanglement is gone. This illustrates why classical physics is often seen as more robust than quantum physics: flipping one (classical) coin would not affect the other coins. Thus, it can come as a surprise to see that entanglement, of all things, can actually help communicate when classical physics cannot.

"Our work is another success of algebraic geometry in quantum information theory," Chen says. "Algebraic geometry considers the sets of common zeros of polynomial systems as objects. It is interesting that many intrinsic concepts in quantum information theory have their natural counterpoints in algebraic geometry. For example, the set of entangled states is known as the complementary of Segre variety, bounded Schmidt rank states can be characterized as the determinant variety. However, only a few papers have looked into this interesting connection so far. Technically, the most difficult part in our work is to calculate the asymptotic rate. In fact, we calculate the channel's transmission rate in terms of bits per channel use. And this transmission rate can be evaluated in the asymptotic limit of infinitely many uses of the channel. Fortunately, we only need to check whether it is zero or not. We then provide an algebraic geometric approach combined with a probabilistic method to answer this question."

According to Runyao Duan [2,3] from the University of Technology, Sidney, Australia, the paper by Chen, Cubitt, Harrow, and Smith provides us with "*a quite accessible description* of their remarkable results obtained earlier about the super-activation of the zero-error classical and quantum capacities: two quantum channels, both with *vanishing zero-error classical capacities*, can be used jointly to achieve a *positive zero-error quantum capacity*. This is the strongest possible super-activation effect known so far in quantum information theory." In fact, as Duan continues, it is rather exciting to see that two channels that cannot transmit single bits can jointly submit quantum bits. After all, a bit is either a 0 or a 1, whereas a quantum bit is any combination of a 0 and a 1 and thus a far more complex object.

"Our study shows the remarkable phenomenon that entanglement between sender and receiver allows perfect communication with a zero capacity channel," Chen says. So how is all of this useful? "To be honest," he continues, "we just proved the existence of two zero (zero-error) capacity quantum channels which can be combined in such a way that the zero-error capacity of the resulting channel is strictly positive. However, some efforts have already been devoted to finding explicit superactive quantum channels. I really hope our results will benefit not only theoretic analysis, but also practical optical communications." And with respect to future technological implications of Chen's research, Duan adds: "this remains an important open problem in general. However, for zero-error communication, super-activation is quite a compelling phenomenon which may well have interesting applications."

[1] A. Niederberger, *Visible and Entangled*, Opt. Photon. Focus **3**, 7 (2008). http://www.opfocus.org/index.php?topic=story&v=3&s=7

[2] R. Duan & Y. Shi, *Entanglement between Two Uses of a Noisy Multipartite Quantum Channel Enables Perfect Transmission of Classical Information*, Phys. Rev. Lett. **101**, 020501(2008).

[3] R. Duan, *Super-Activation of Zero-Error Capacity of Noisy Quantum Channel*, arXiv:0906.2527 (2009).

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Jianxin Chen, Toby S. Cubitt, Aram W. Harrow & Graeme Smith, **Entanglement can Completely Defeat Quantum Noise**, Physical Review Letters **107**, 250504 (2011).