RTT TECHNOLOGY TOPIC
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Smart Quantum From Space

In this month's technology topic we study how space adds value to quantum networks and how quantum networks in space potentially enable secure end to end connectivity.

This is one of the topics we address in depth on our 5 day workshop on LEO, MEO and GSO system and service integration presented in association with the Continuing Education Institute. To view the agenda and book a place on the workshop, follow the link

https://www.cei.se/course-820-leo-meo-and-gso-system-and-service-integration-group.html

Read on

Historians cite the American Civil War (1861-1865) as the first documented example of the widespread use of electronic interception gathering intelligence and generating disinformation by tapping into the telegraph cables.

160 years later, network interception remains a critical concern for defence agencies and for commercial entities exposed to communication risk. This includes more or less all businesses everywhere. At a personal level, none of us like having our bank accounts emptied by a malicious third party.

Quantum key distribution is promoted as an effective way of securing end to end communication channels both for authentication and encryption.

Authentication is the process by which a network ensures that every node in an end to end channel can be trusted. Encryption means that even if a message is intercepted, it cannot be read. A quantum key can be used for authentication and then used as a seed for conventional AES encryption so the two processes can be coupled. The underlying problem with all quantum systems is noise and a loss of coherence in the channel.

Quantum authentication relies on the quantum phenomena of entanglement. Quantum encryption relies on the quantum phenomena of superimposition which is also the basis of quantum computing.

The two phenomena are related but separate with both processes stemming from the ability of a charged particle, an ion, electron or photon to exist in three states, positively charged, negatively charged or positively and negatively charged. This ability to move from binary to three state computation makes Quantum computers powerful and secures quantum encryption from brute force attack.

Entanglement is the phenomena whereby a charged particle becomes entangled with another charged particle. If the charged particles are separated and one of the entangled particles changes state then the other also changes state instantaneously.

This theoretically breaks the rules of classical physics that state that nothing can travel at faster than the speed of light and led Einstein to describe the phenomena as spooky action at a distance. 100 years on there is still no consensus as to what is happening. The happy thought is that we can talk to Mars in real time rather than waiting for twenty minutes for radio waves to arrive. Sadly this is not going to be possible for the immediate future and little progress will be made until the laws of physics are rewritten and understood.

In the meantime entanglement and superimposition can be used to improve network security and the easiest starting point is optical networks using photons.

To produce an entangled photon, you take one energetic photon, and using a laser, split it into two photons with a lower charge inside a crystal of beta-barium borate. The two photons will come out naturally entangled with each other. To create an eight-photon entanglement, feed the photons through beam splitters and have them arrive at exactly the same time to produce multiple entangled pairs. Make sure you can tell which are photons are entangled and which are untangled and you have arrived at the point where you can exchange a set of quantum keys.

Photons and electrons are different. Electrons have a tiny mass and transmit energy by bumping into each other producing an energy wave moving through a medium, a copper wire for example, at the speed of light. The excitation state of an electron is an up or down vibration or both at the same time which is how a three state qubit can be matched to the electron. Electrons do move but slowly, typically at walking pace down a cable which is rather sweet.

Photons are massless and are energy particles that move at the speed of light in free space (slightly slower in fibre). They exist in three states, a state of left hand spin, a state of right hand spin or a state in which they are spinning in both states at the same time or more precisely all states at the same time. The spin state is therefore a description of the polarisation of the photon. Intriguingly the left hand and right hand spin states produce a rotational energy, a torque effect, which can be detected by a MEMS (micro electrical mechanical system) sensor. In most other respects, light waves behave in the same way as radio waves with similar filter and bandwidth ratio constraints.

The problem is that the process of entanglement between two photons splits the energy between the two entangled photons at either end of the communication channel; an 8 photon entanglement divides the energy by a factor of 8. This means that noise on the channel, which for photons includes solar noise, becomes a problem. Additionally any loss of coherence in the channel will result in detection uncertainty.

Quantum key distribution can therefore be made to work in space to set up inter satellite and inter constellation trusted nodes but is hard though not impossible to implement over uplinks and downlinks.

A QKD exchange was made over the Micius satellite early in 2018. Named after the Chinese philosopher Mozi, (also known as Micius 470-391BC), the satellite was placed in a sun synchronous orbit at 500 kilometres with optical uplinks from three ground stations, one in Tibet at 4000 metres, one in Beijing and one in Vienna.

The experiment created entangled pairs of photons on the ground at a rate of 4,000 per second which were then beamed to the satellite, which passed overhead every day at midnight. The other photon stayed on the ground. The experiment lasted 32 days and involved millions of photons with 911 positive results, a correlation rate that allowed the Chinese/Austrian team to claim that a Quantum Key had been distributed via satellite between ground stations over 7000 kilometres apart. The channel loss over the uplink was calculated to be between 41 and 52 dB and would have been higher if the ground stations had been at a lower altitude.

The real value of the Micius project was therefore to demonstrate that transmission and detection of photonic Qubits over an earth to space link was at least possible if not exactly easy.

Once in space, decoherence is minimal which means that setting up trusted nodes is relatively straight forward. An end to end channel would however need to get back to earth and then into terrestrial fibre with a need to achieve high precision time synchronisation and frequency locking to enable the key to be read.

Similar albeit smaller scale experiments are ongoing led by the University of Strathclyde using CubeSATS. This includes trials and test of QKD (entangled photons with a known spin condition) and a protocol known as Measurement Device Independent QKD (MDI QKD).

MDI-QKD measures the correlations in the signal between the sender and receiver rather than directly measuring the spin states of individual photons. For example in MDI-QKD, if there is an instantaneous change of phase or polarisation of the carrier at both ends of a link (or at both ends of multiple links) then is a correlation which can be registered as a+1 or-1.

QKD and/or MDI QKD can be implemented either by one satellite sending a QKD or MDI-QKD message on a dual optical downlink to two ground stations or two satellites (or more) sending the MDI-QKD or entangled (QKD) message simultaneously on a downlink to two or more ground stations. Conceptually this is similar to intensity modulation (used in LED transceivers in the 800 and 900 nanometre bands, sometimes called Off On Keying OOK) versus coherent modulation/demodulation (phase, frequency, amplitude or polarisation/spin state).

In both cases two links (and in the second case two or more links) are being used, both or all of which will suffer from noise and channel distortion. Note that downlinks are inherently better than uplinks where close to ground distortion causes pointing loss close to the transmitter. As a general rule this will mean an additional loss of between 10 and 20 dB on the uplink.

But all being well and having established the link as secure, a secure message exchange can take place either over a radio link or optical link with the option to use the QKD or MDI-QKD as the seed for the message encryption which can be done using conventional binary encoding. With QKD, any attempt to read a Qubit encoded string during transmission will destroy the information and it should be obvious that an interception attempt has been made.

However it is necessary to understand that by their very nature, quantum based authentication systems (and encryption systems) are sensitive to noise. Although space does not have material atmospheric loss or coherence loss, other effects such as radiation and solar noise and temperature cycling (typically -10 to +40 degrees every 90 minutes for LEOS) can cause hardware errors or transceiver stability issues. Optical coatings can become unstable in a vacuum and all components will have had a thorough shake down during launch.

Hardware, either the whole satellite or optical and electronic and or RF hardware inside the satellite can also be deliberately destroyed. Optical systems are vulnerable to high power lasers and electronics can be deliberately exposed to high levels of ionising radiation, the modern equivalent of the Confederates cutting through Yankee telegraph cables.

In summary, smart quantum from space will initially struggle to scale technically and commercially but the potential is huge particularly when you consider that QKD over terrestrial fibre is theoretically constrained to a few hundred kilometres and practically constrained to a few tens of kilometres whereas links spanning tens of thousands of kilometres could be deployed in space.

The need to maintain coherence over long fibre links linking multiple terrestrial telescopes is leading to improvements but terrestrial fibre remains a non-ideal medium for transferring quantum data and its associated distributed timing requirements. A loss of 3dB is potentially tolerable but would imply a repeater every 15 kilometres assuming a standard fibre loss of 0.2db/km.

At some stage in the future we may take integrated terrestrial and space Quantum Networks for granted but only as and when we have better control of noise, loss and coherence in fibre and in free space channels subject to atmospheric distortion. Once we are in space, distance becomes less of an obstacle though 'faster than light' communication remains for the moment in the realms of science fiction.

Though science fiction has a habit of becoming science fact……….. eventually.

Resources including noise reduction techniques
https://jqi.umd.edu/news/quantum-matchmaking-new-nist-system-detects-ultra-faint-communications-signals-using-principles

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00 44 7710 020 040