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Next-Generation Quantum Communication

In the era of instant data exchange and growing risks of cyberattacks, scientists are seeking secure methods of transmitting information. One promising solution is quantum cryptography – a quantum technology that uses single photons to establish encryption keys. A team from the Faculty of Physics at the University of Warsaw has developed and tested in urban infrastructure a novel system for quantum key distribution (QKD). The system employs so-called high-dimensional encoding. The proposed setup is simpler to build and scale than existing solutions, while being based on a phenomenon known to physicists for nearly two centuries – the Talbot effect. The research results have been published in prestigious journals: “Optica Quantum”, “Optica”, and “Physical Review Applied”.

“Our research focuses on quantum key distribution (QKD) – a technology that uses single photons to establish a secure cryptographic key between two parties,” says Dr. Michał Karpiński, head of the Quantum Photonics Laboratory at the Faculty of Physics, University of Warsaw. “Traditionally, QKD employs so-called qubits – the simplest units of quantum information. While this method is already well tested, it does not always meet the requirements of more demanding applications. That’s why researchers are now working on multidimensional encoding. Instead of qubits, which yield one of two measurement outcomes, we use more complex quantum states that can take on multiple values.”

At the Quantum Photonics Laboratory, researchers focus on time-bin superpositions of photons – situations where a photon is neither “earlier” nor “later” but exists in a combination of these states. The detection time of a single photon in such a superposition yields a random outcome. Such a state encodes information using the relation between earlier and later pulses, i.e., in the phase of the light wave.

“Until now, efficient detection of superpositions of two pulses – earlier and later – was possible. We went a step further: we are interested in cases with more time bins, ranging from two to four or even more,” adds Dr. Karpiński.

The Temporal Talbot Effect

The researchers drew inspiration from the Talbot effect – a classical optics phenomenon first described in 1836 by Henry Fox Talbot, a pioneer of photography.

“When light passes through a diffraction grating, its image repeats itself at regular intervals – as if it ‘revives’ at a certain distance. Interestingly, the same effect occurs not only in space but also in time, provided that a regular train of light pulses propagates in a dispersive medium such as an optical fiber,” explains Maciej Ogrodnik, a PhD student at the Faculty of Physics, UW.

“Thanks to the space-time analogy in optics, we can apply the Talbot effect to short light pulses, including single photons – thereby gaining new capabilities for analyzing and processing quantum states. In our case, a sequence of light pulses acts like a diffraction grating and can ‘self-reconstruct’ in time under dispersion after traveling some distance in an optical fiber. Moreover, the way pulses interfere depends on their phase, which allows us to detect different types of superpositions.”

The UW research team developed an experimental four-dimensional QKD system.

“Importantly, the entire setup is built using commercially available components. The key trick is that the system requires only a single photon detector to register superpositions of many pulses – instead of a complex network of interferometers,” says Adam Widomski, a PhD student at the Faculty of Physics, UW.

“This significantly reduces the complexity and cost of the measurement system. Moreover, our method does not require separate, often time-consuming and challenging calibration of the receiver.”

“Traditionally, to detect phase differences between pulses, we use a multi-interferometer setup – something like a tree, where pulses are split and delayed. Unfortunately, such systems are inefficient, since some measurement outcomes are useless. The efficiency drops with the number of pulses, and the receiver requires precise calibration and stabilization,” explains Ogrodnik.

“The advantage of our method is its high efficiency, as all photon detection events are useful. The drawback is relatively high measurement error rates. However, these do not prevent QKD, as we showed in collaboration with researchers working on the theory of quantum cryptography. Furthermore, we do not need to rebuild the setup for different dimensions of superpositions – we can detect 2D and 4D superpositions without changing hardware or stabilizing the receiver. This is a huge advantage compared to earlier methods,” adds Widomski.

Not Only Speed, But Also Security

The researchers tested their solution both in laboratory optical fibers and in the fiber infrastructure of the University of Warsaw over distances of several kilometers.

“Thanks to the new method using the temporal Talbot effect, we successfully demonstrated QKD with two- and four-dimensional encoding, using the same transmitter and receiver. Despite errors inherent to the simple experimental approach, our results confirm the higher information efficiency of the system resulting from high-dimensional encoding,” says Widomski.

The main advantage of QKD is its theoretical security, which can be proven under basic assumptions. For this reason, from the start of the project, UW researchers collaborated with groups in Italy and Germany specializing in QKD security proofs.

“A closer analysis shows that the standard description of many QKD protocols is incomplete, which attackers could exploit. Unfortunately, our method shares this vulnerability. We took part in efforts to solve this issue. Our collaborators found that a certain modification of the receiver allows for collecting more data, thus eliminating the vulnerability. The security proof of the new protocol was published in *Physical Review Applied*, and in our latest paper we discuss its application to our experiment,” says Ogrodnik.

This research not only produced new scientific results but also built expertise in cutting-edge quantum photonic technologies at the Faculty of Physics, UW.

The project was carried out within the QuantERA international cooperation program on quantum technologies, coordinated by the National Science Centre (NCN, Poland). The research used infrastructure of the National Laboratory for Photonics and Quantum Technologies (NLPQT) at the Faculty of Physics, University of Warsaw (nlpqt.fuw.edu.pl).

Faculty of Physics, University of Warsaw

Physics and astronomy at the University of Warsaw date back to 1816, within the Faculty of Philosophy. In 1825, the Astronomical Observatory was established. Today, the Faculty of Physics comprises the Institutes of Experimental Physics, Theoretical Physics, Geophysics, the Chair of Mathematical Methods in Physics, and the Astronomical Observatory. Research spans nearly all areas of modern physics, from the quantum to the cosmological scale. The Faculty employs over 250 academic staff and educates more than 1,100 students and about 170 PhD candidates. In Shanghai's Global Ranking of Academic Subjects, the University of Warsaw ranks among the top 300 worldwide in physics.

SCIENTIFIC PUBLICATION:

Maciej Ogrodnik, Adam Widomski, Dagmar Bruß, Giovanni Chesi, Federico Grasselli, Hermann Kampermann, Chiara Macchiavello, Nathan Walk, Nikolai Wyderka, Michał Karpiński, High-dimensional quantum key distribution with resource-efficient detection, *Optica Quantum* 3, 372–380 (2025)
<https://doi.org/10.1364/OPTICAQ.560373>

Adam Widomski, Maciej Ogrodnik, Michał Karpiński, Efficient detection of multidimensional single-photon time-bin superpositions, *Optica* 11, 926 (2024) <https://doi.org/10.1364/OPTICA.503095>

Federico Grasselli, Giovanni Chesi, Nathan Walk, Hermann Kampermann, Adam Widomski, Maciej Ogrodnik, Michał Karpiński, Chiara Macchiavello, Dagmar Bruß, Nikolai Wyderka, Quantum key distribution with basis-dependent detection probability, *Physical Review Applied* 23, 044011 (2025),
<https://doi.org/10.1103/PhysRevApplied.23.044011>

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GRAPHIC MATERIALS:

FUW251001b_fot01

https://www.fuw.edu.pl/tl_files/press/images/2025/FUW251001b_fot01.png

Detection of time-bin superpositions with the temporal Talbot carpet (visualisation: Maciej Ogrodnik, University of Warsaw).