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A world-record achievement in the 100-kilometer practical quantum secure direct communication rate

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Recently, Long *et al.* [1] at the Beijing Academy of Quantum Information Sciences, in collaboration with the partners, proposed the theory of one-way quantum secure direct communication (QSDC) and successfully developed a practical system. This achievement set a world record for long-distance stable transmission, demonstrating a rate of 2.38 kbps at a distance of 104.8 km over 168 hours.

QSDC was first proposed by Long and Liu in 2000 [2], with the goal of enabling secure and reliable communication over a quantum channel subject to both noise, loss, and eavesdropping [3–5]. It features characteristics such as eavesdropping detection, eavesdropping prevention, compatibility with existing networks, simplified management processes, and covert transmission [6], making it highly promising for next-generation secure communication [7]. The theory of QSDC has evolved rapidly, and many variants of the QSDC protocol have been proposed [8–27]. To mitigate vulnerabilities in quantum devices, researchers have developed innovative protocols including: (i) measurement-device-independent QSDC (MDI-QSDC) [9–11], which enhances security at detection nodes by outsourcing Bell-state measurements to untrusted third parties; (ii) reference-device-independent QSDC (RDI-QSDC) [12], which reduces reliance on receiving devices through statistical characterization of signals; (iii) passive-source QSDC [13–15], which eliminates source-side security vulnerabilities by avoiding active modulation operations; and (iv) device-independent QSDC (DI-QSDC) [16–19], which achieves unconditional security guarantees by verifying Bell inequality violations to circumvent assumptions about source and detector. In addition, quantum error-correcting codes have been integrated into QSDC frameworks [20], significantly improving robustness against channel noise. And many variants of the QSDC protocol [21–27] have been proposed to extend the family of QSDC. Meanwhile, experimental development [28, 29] of QSDC has advanced rapidly, gradually extending from long-distance fiber-based communication scenarios [30–35] to free-space communication [36] and networking [37, 38]. A latest experimental breakthrough [39] has successfully demonstrated a 300-kilometer fully-connected QSDC network, marking a crucial step toward transitioning QSDC from theoretical frameworks to practical long-distance large-scale quantum communication. Mature QSDC schemes enable the transmission of private information from sender to receiver by sending quantum states over a round-trip transmission [4, 40]. These schemes offer advantages such as eliminating the need for basis reconciliation, preventing information leakage before eavesdropping detection, and enabling quantum-integrated sensing and communication [41]. However, achieving 100 km QSDC requires transmitting quantum states over 200 km, and improving communication performance under device limitations remains challenging. These two comprehensive reviews [6, 42] provide valuable insights into the latest progress in QSDC.

In QSDC, how can we address the high losses caused by two-way transmission of quantum states? One solution is to use the one-way protocol [43–47]. Long *et al.* [1] proposed a one-way quasi-QSDC protocol for simultaneous transmission of information and key exchange (STIKE), which merges information transfer and key exchange within the same photonic quantum states. The protocol has the following key features: (i) One-way quantum state transmission. Privacy information can be transmitted with only a one-way transmission of quantum

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states between the communicating parties. (ii) Robustness against loss and noise. By integrating forward error correction coding and spreading spectrum, STIKE mitigates channel losses (e.g., 20 dB over 100 km of fiber) and errors. The spreading spectrum technique dynamically adjusts redundancy based on channel conditions, ensuring reliable communication even under high attenuation. (iii) Secure key recycling. The method of increasing channel capacity using masking involves encrypting ciphertext with locally generated random numbers, thereby reducing key consumption and enhancing security. Untriggered photons retain encrypted keys, which can be recycled through an optimized balancing mechanism of key depletion and replenishment.

The authors demonstrated STIKE over 104.8 km of standard fiber, achieving a real-time secure rate of 2.38 kbps with a quantum bit error rate (QBER) of 3.6%, thus setting a record for both QSDC distance and rate. For shorter distances (50.3 km), rates up to 34.08 kbps were achieved, which highlighting the scalability of the protocol. The protocol's stability was further validated through week-long tests, demonstrating resilience against environmental fluctuations. Notably, at 80 km, STIKE information transmission rate surpasses traditional two-way QSDC by three orders of magnitude, underscoring its efficiency.

The one-way architecture of STIKE eliminates the need for two-way transmission in QSDC, simplifying its hardware implementation. Additionally, its compatibility with free-space channels expands its potential applications to satellite-based or mobile quantum networks.

The STIKE protocol bridges the gap between theoretical QSDC and its practical implementation. By enabling the simultaneous transmission of information and key exchange with unprecedented distance and stability, it accelerates the transition toward secure quantum communication infrastructures. Future advancements in device performance and protocol optimization will further unlock its potential, paving the way for a quantum-secured global network [48, 49].

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