TECHNISCHE UNIVERSITÄT DRESDEN

6G-life

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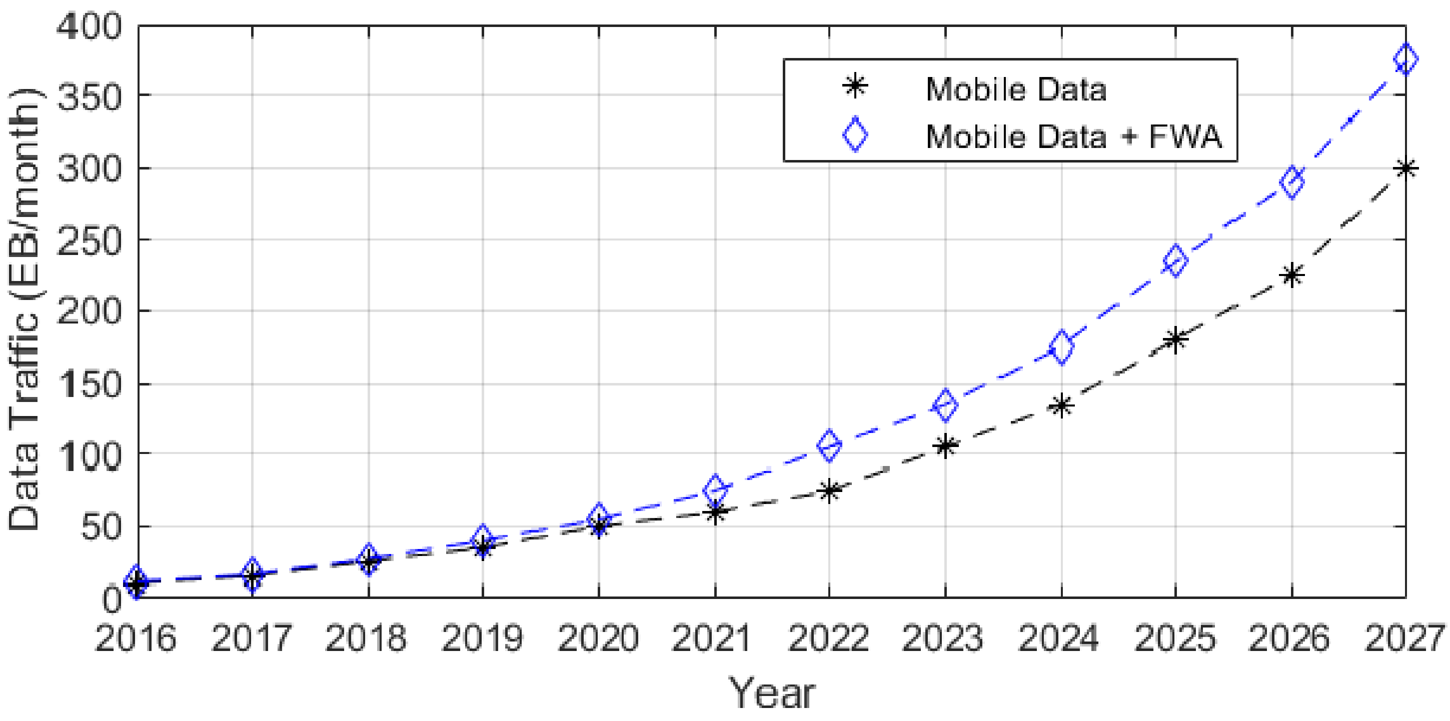
Towards Quantum Semantic Communications: A Framework for Integrating Quantum and Semantic Technologies

Quantum Breakfast
TU Braunschweig (via Zoom)
Dresden // 08.05.202

Content

Motivation – Exponential Data Growth



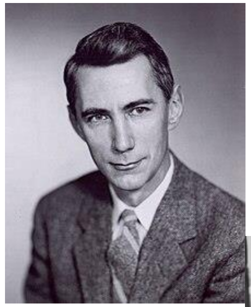
[1] Ericsson. (2021). Ericsson Mobility Report. [Online]. Available: https://www.ericsson.com/4ad7e9/assets/local/reports papers/mobilityreport/documents/2021/ericsson-mobility-report-november-2021.pdf

Motivation

How can we communicate more efficiently over an increasingly heterogeneous network?

State-of-the-Art

Conventional Communications



Claude Elwood Shannon

Warren Weaver

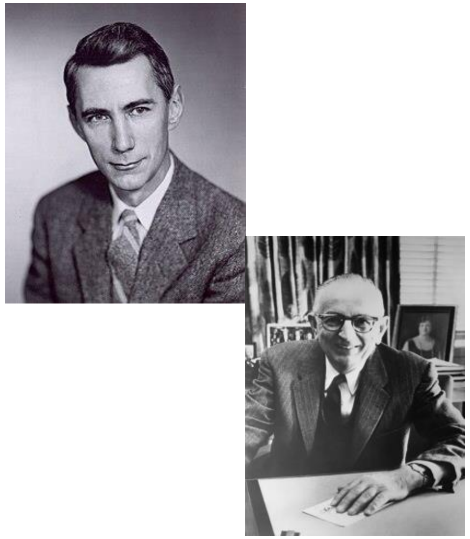
Level A. How accurately can the symbols of communication be transmitted? (The technical problem.)

Level B. How precisely do the transmitted symbols convey the desired meaning? (The semantic problem.)

Level C. How effectively does the received meaning affect conduct in the desired way? (The effectiveness problem.)

[1] C. E. Shannon, A mathematical theory of communication, The Bell system technical journal 27 (1948) 379–423.

Semantic Communications



Level A. *How accurately can the symbols of communication be transmitted? (The technical problem.)*

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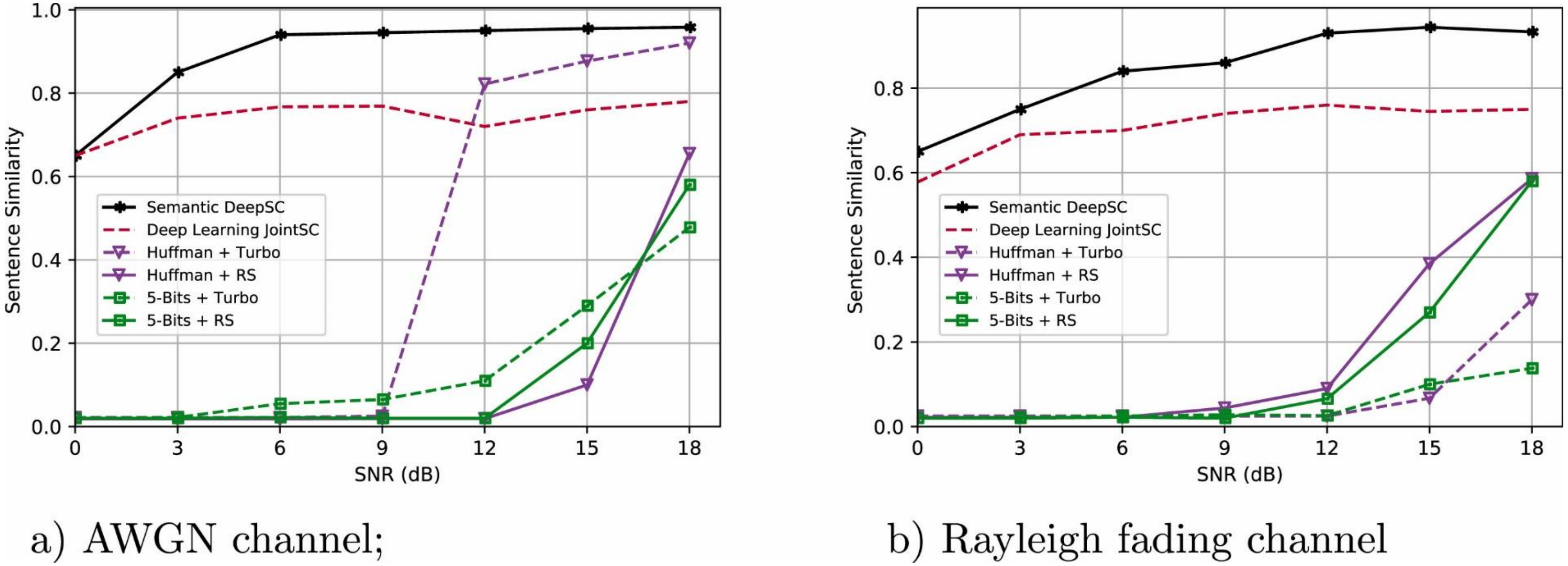
[1] C. E. Shannon, A mathematical theory of communication, The Bell system technical journal 27 (1948) 379–423.

State-of-the-art: Developments in Semantic Communication

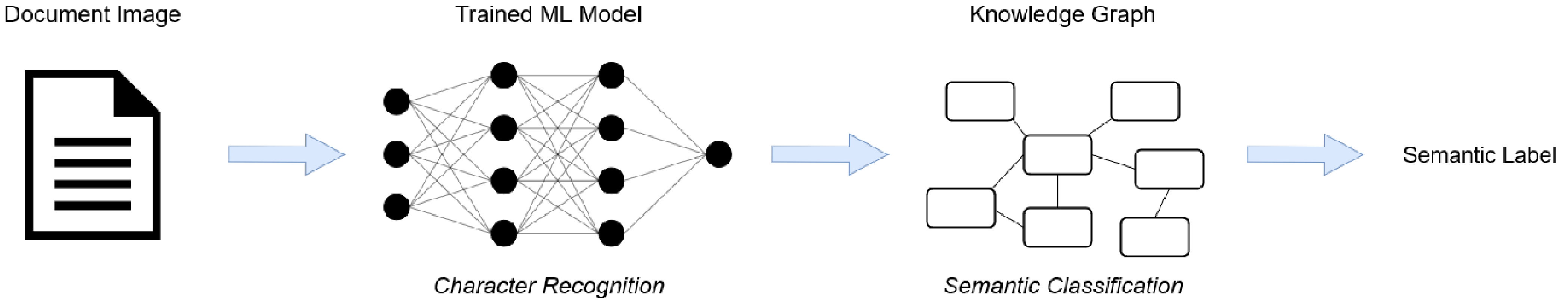
Based on a study of text transmission



- Traditional encoding methods show zero performance at low SNR
- Semantic encodings show the gain in the low SNR, and
- Robustness with increasing noise

[2] Xie H, Qin Z, Li GY, Juang BH. Deep learning enabled semantic communication systems. IEEE Transactions on Signal Processing. 2021 Apr 7;69:2663-75.
[3] Strinati, Emilio Calvanese, and Sergio Barbarossa. "6G networks: Beyond Shannon towards semantic and goal-oriented communications." Computer Networks 190 (2021): 107930.

Leveraging Hybrid ML-KG Systems for Effective Semantic Communication



Efficiency and Performance

- 40% reduction in network traffic
- Decreased error rates
- Substantial reductions in the volume of communicated entities and attributes (47% and 17%, respectively)
- This approach can reduce the conveyed information by up to 91%, addressing increasing data demands more efficiently

[4] D. Wheeler and B. Natarajan, "Engineering Semantic Communication: A Survey," in *IEEE Access*, vol. 11, pp. 13965-13995, 2023, doi: 10.1109/ACCESS.2023.3243065

Limitations and Challenges

Scalability of Knowledge Graphs (KGs)

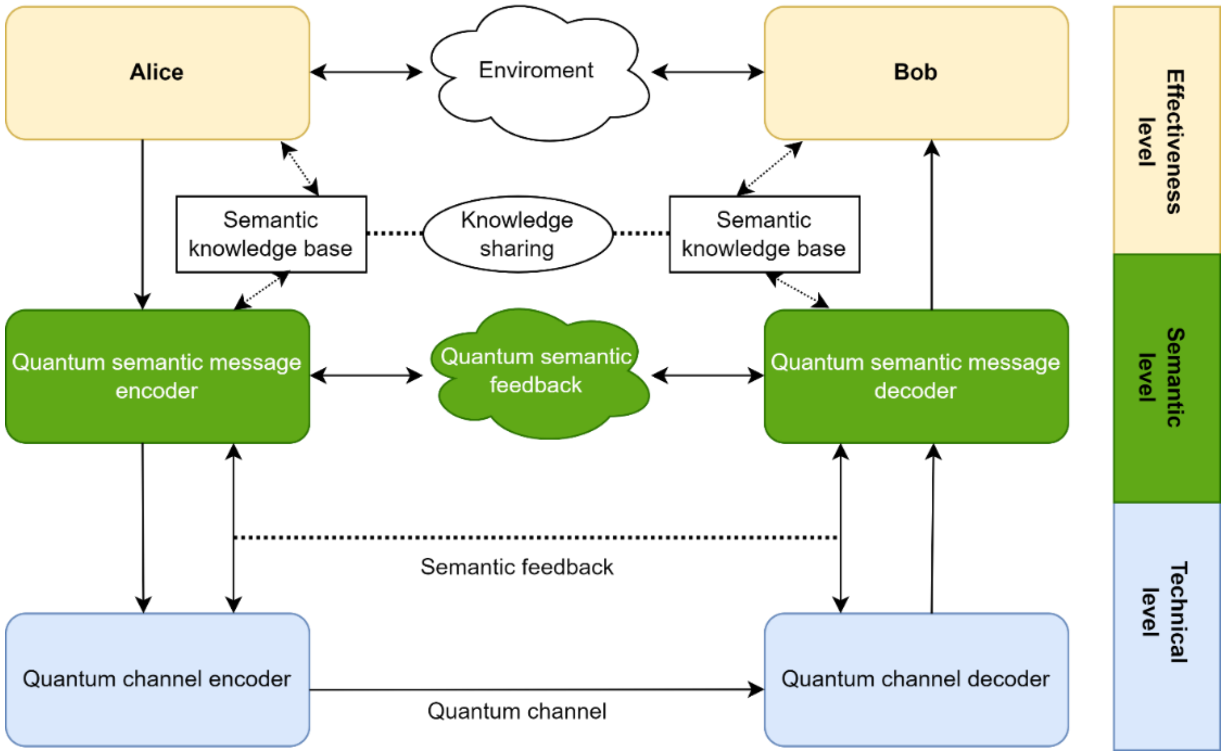
- Increasing size of graph
- Difficult to manage in real-time systems
- Computational – time complexities

Requires scalable methods and techniques!

Integration of Quantum Technologies to Semantic Communications

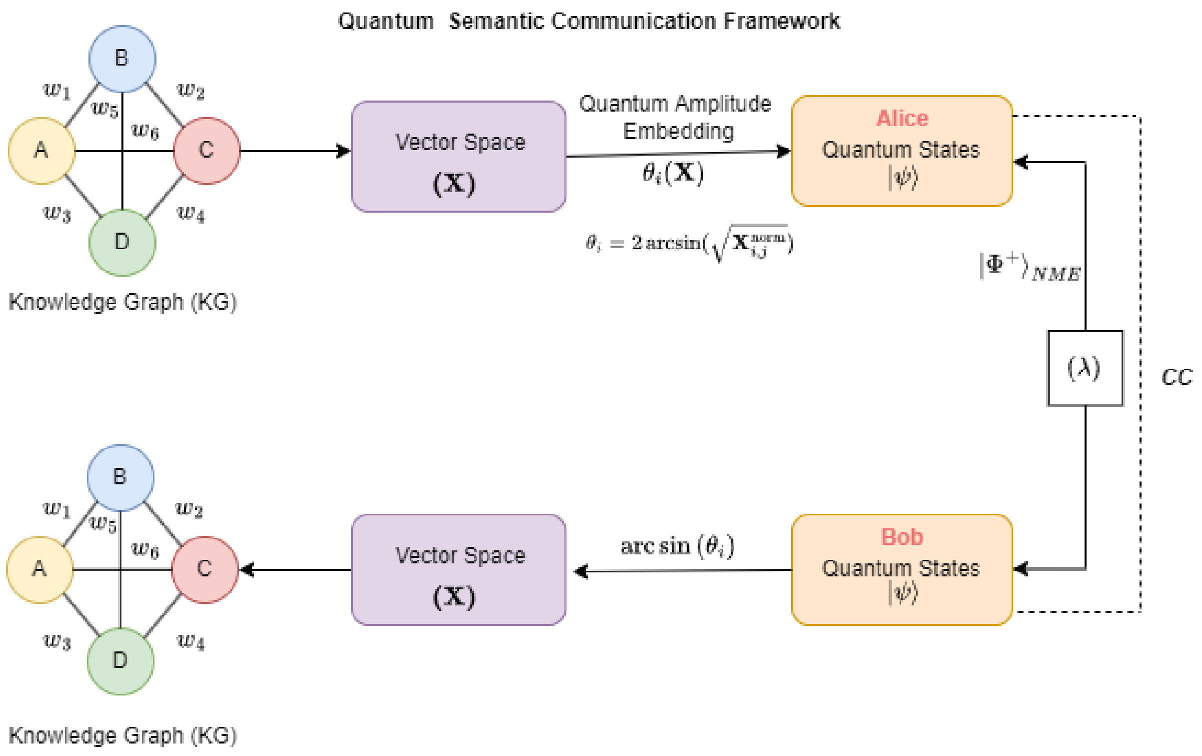
Our Proposal

Integration of quantum communication model to the semantic level



[5] Nunavath, N., Strinati, E. C., Bassoli, R., & Fitzek, F. H. (2024, October). Pragmatic Semantic Communication Through Quantum Channel. In *2024 3rd International Conference on 6G Networking (6GNet)* (pp. 189-195). IEEE.

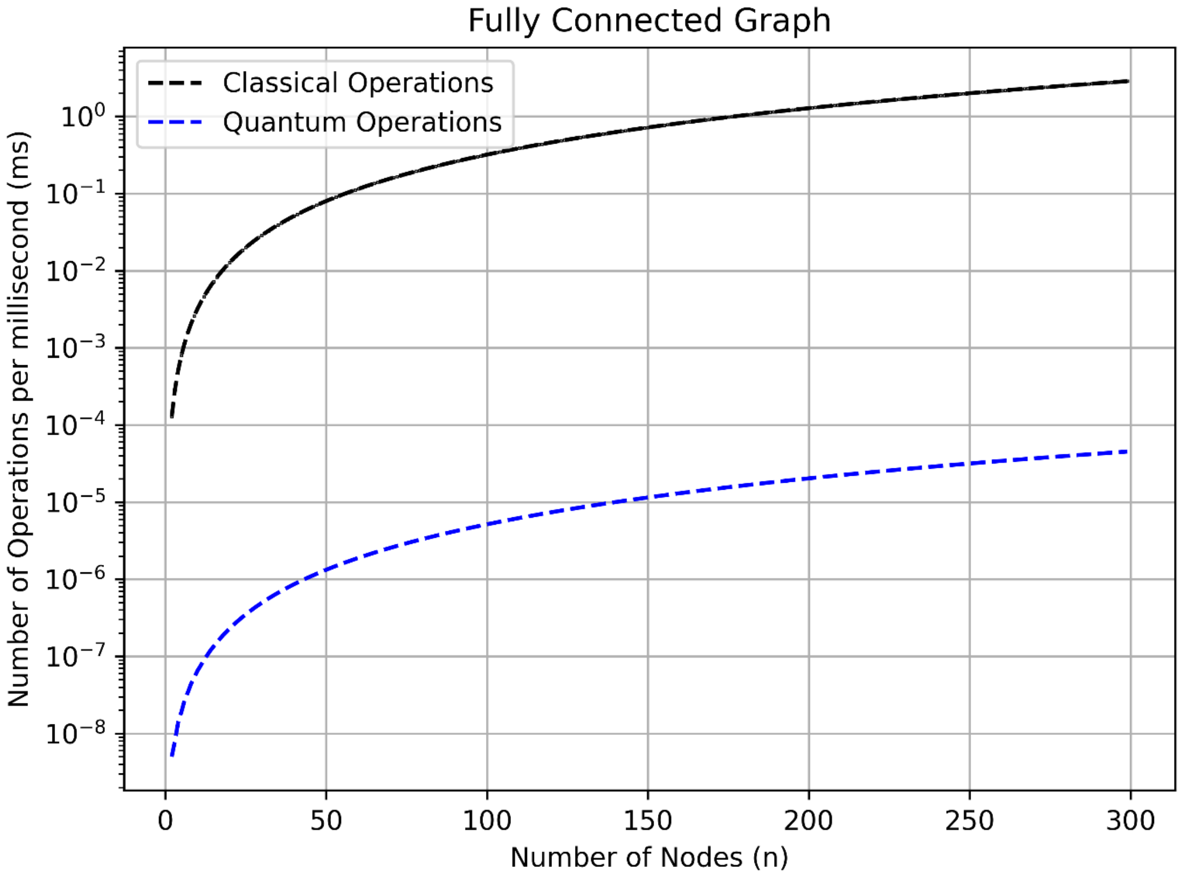
Quantum Semantic Communication Framework (proof of concept)



Implementation Process of Quantum Semantic Communication

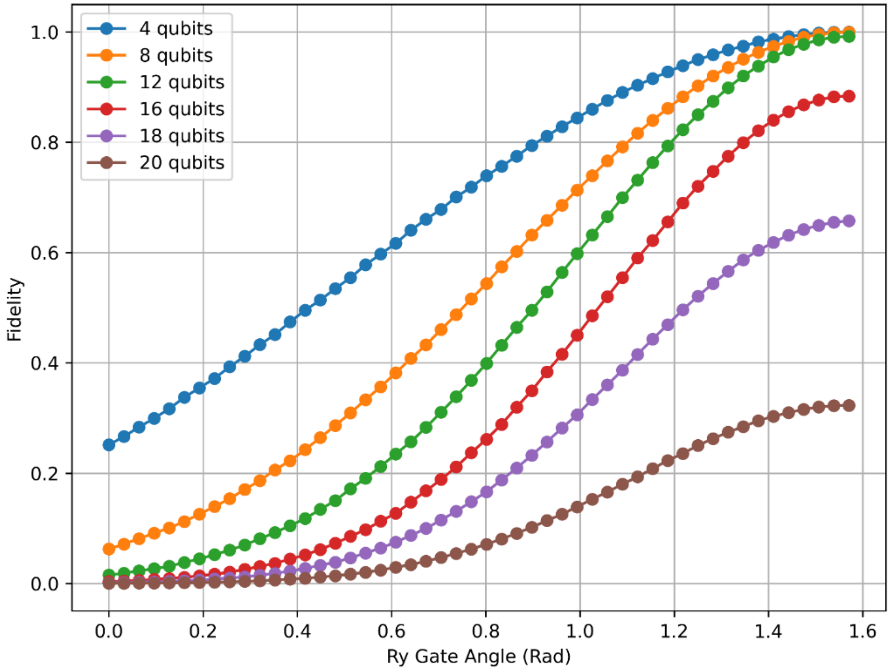
[6] Nunavath, N., Habibie, M. I., Strinati, E. C., Bassoli, R., & Fitzek, F. H. (2024, September). Quantum Semantic Communications for Graph-Based Models. In *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)* (pp. 871-875). IEEE.

Time Complexity Analysis – Polynomial Gain

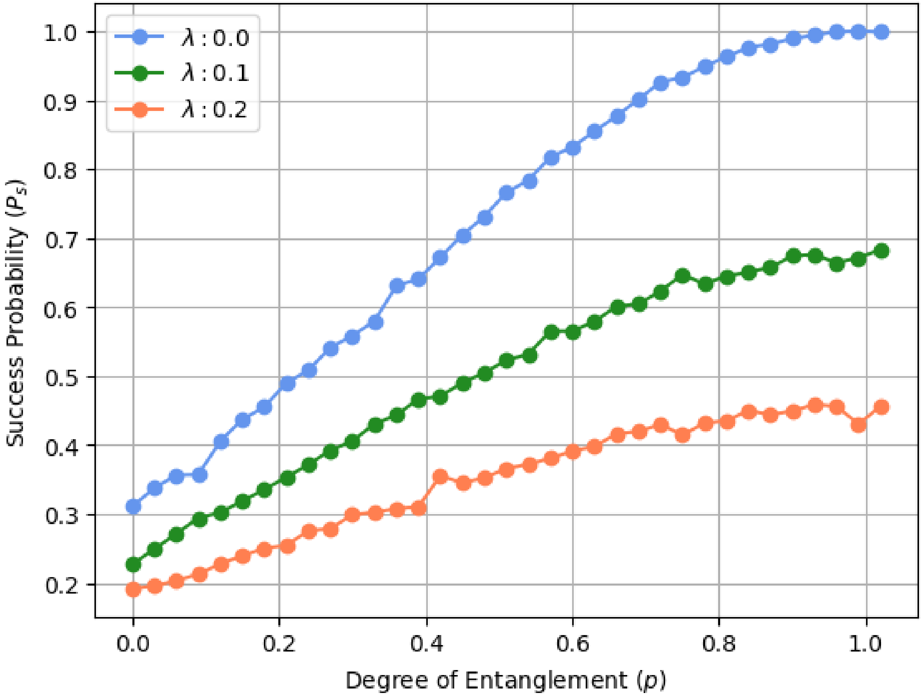


The tradeoffs between increasing nodes in a graph vs computational complexity (plotted in log scale).

Feasibility of Quantum State Transmission

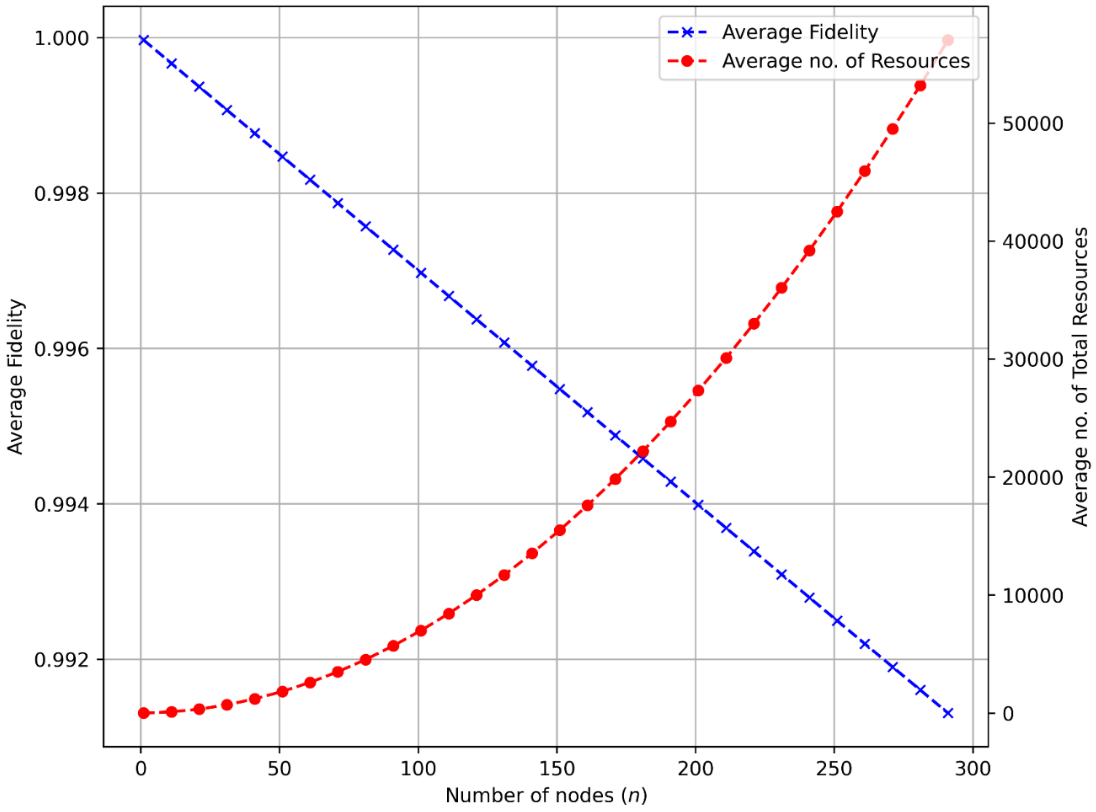


(1) Amplitude damping noise



(2) Success probability of semantic decoding

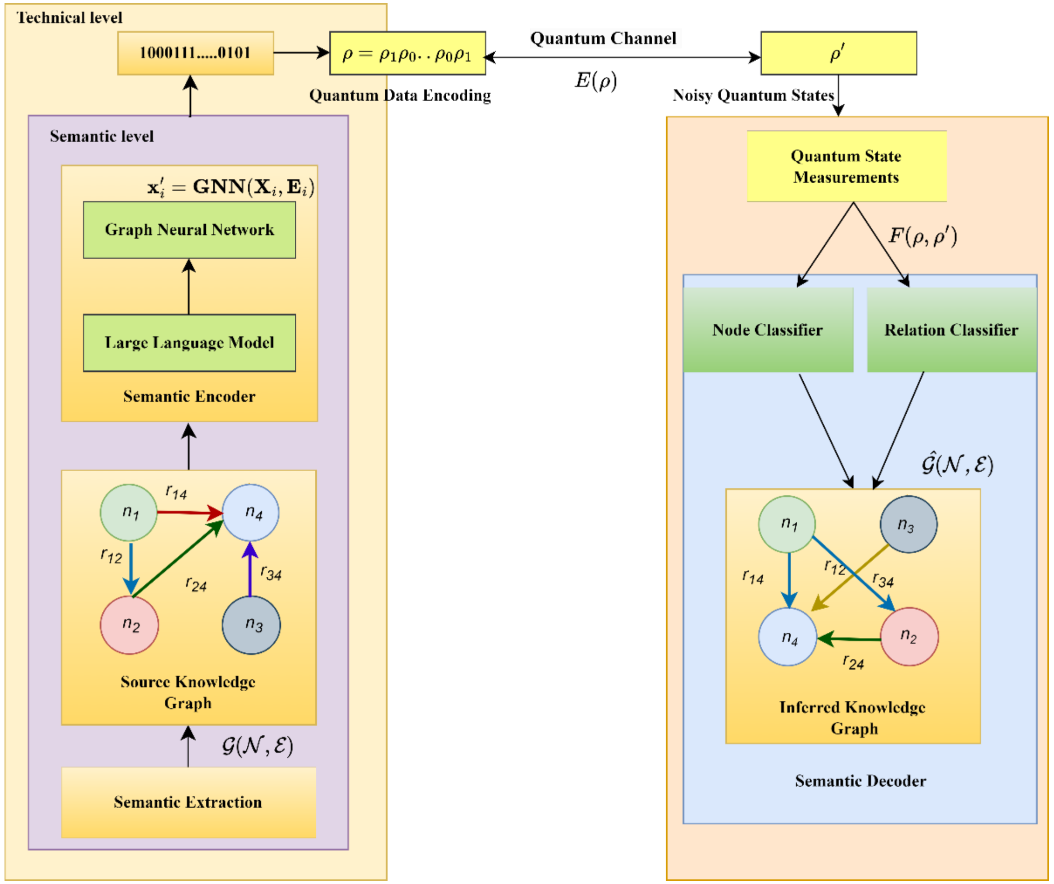
Scalability Analysis



Resources – studied based on superconducting technology

- Single-qubit operations
- Quantum state measurements
- Two-qubit operations (entanglement distribution)

Proposed Quantum Semantic Communication Framework

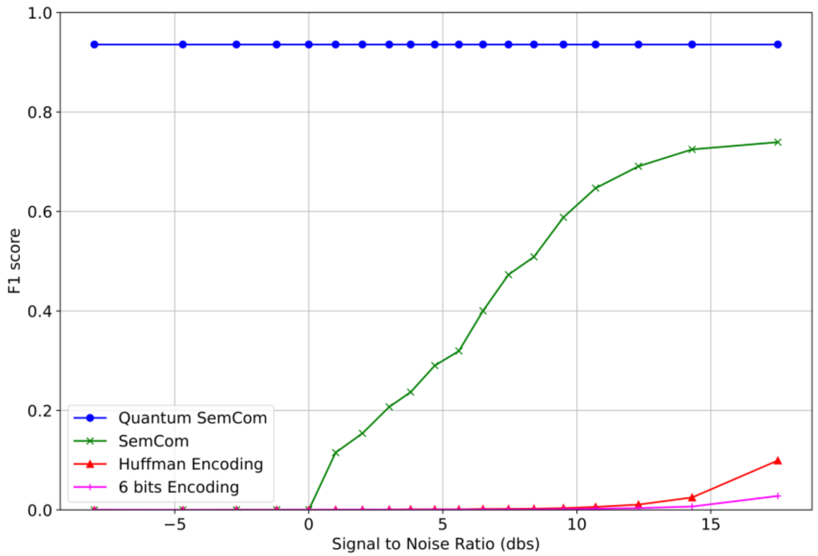


Schematic diagram of quantum semantic communications

[7] Nunavath, N., Hello, N., Strinati, E. C., Bassoli, R., & Fitzek, F. H. (2024). Towards Quantum Semantic Communications: A Framework for Integrating Quantum and Semantic Technologies. *Authorea Preprints*.

Performance Analysis

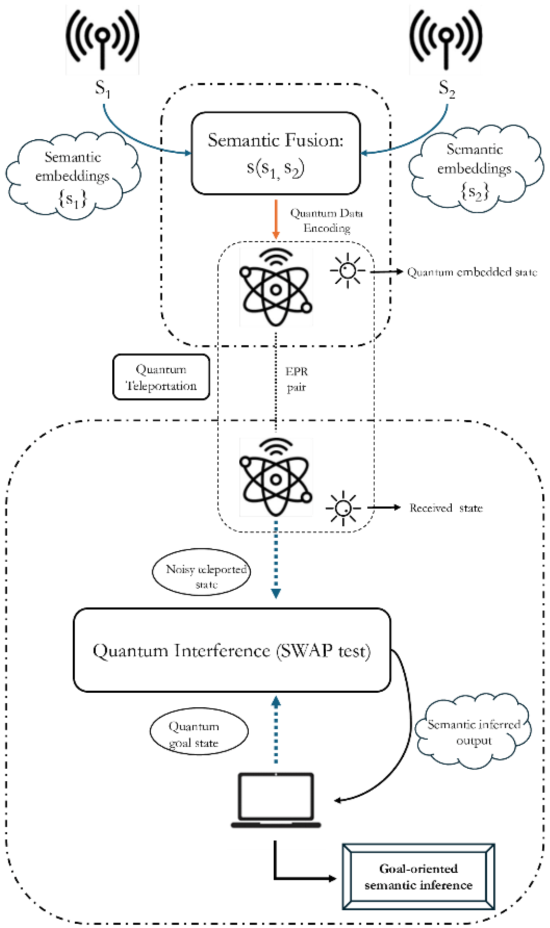
Performance evaluation between our proposed quantum semantic communication approach and semantic communication methods



- ✓ This comparison highlights the advantage, measured by the F1 score as a function of signal-noise ratio (SNR)
- ✓ The quantum SemCom approach demonstrates high performance in the knowledge graph recovery and achieves an F1 score of 0.935
- ✓ In contrast, the SemCom over AWGN channel approach indicated by the green curve fails to reach this maximal performance, hits a score of 0.74 for an SNR of 17.5 dbs, and still outperforms traditional approaches, like Huffman encoding and 6-bit encoding over AWGN channel

Quantum Semantic Sensing (QSS) Architecture

A Novel Quantum Semantic Sensing (QSS) Architecture

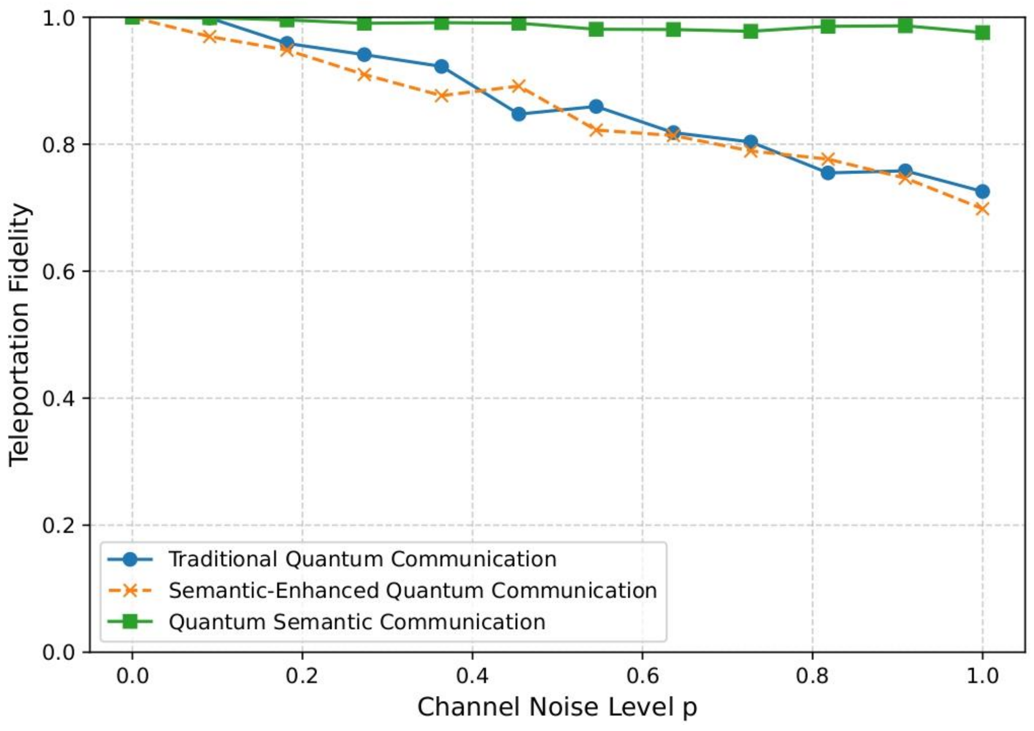


QSS Model

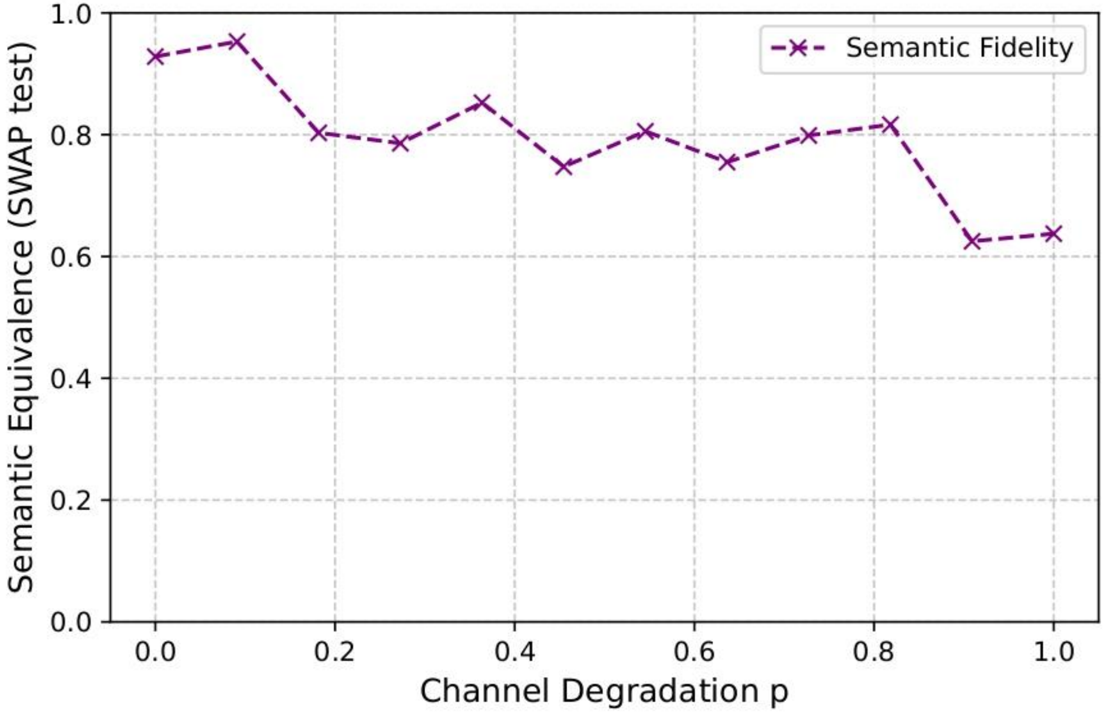
i. Sensing from S1 and S2 and Semantic Embedding via Fusion
ii. Quantum Data Encoding
iii. Quantum Teleportation
iv. Semantic Interference and Output

[8] Nunavath, Nikhitha, Vignesh Raman, Emilio Calvanese Strinati, Riccardo Bassoli, and Frank H. P. Fitzek,. "A Quantum Semantic Communication Architecture for IoT Sensingin 6G Networks" (submitted to IEEE Standards Magazine).

Performance Analysis

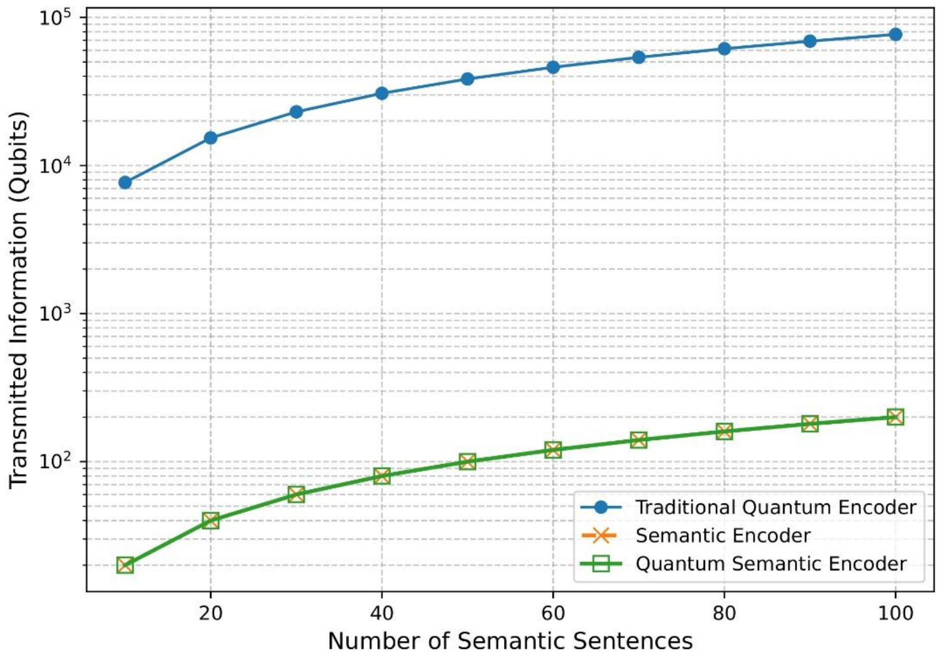


(1) Teleportation fidelity comparison



(2) Semantic fidelity versus channel degradation p using SWAP test inference

Resource Scalability



QSS's scalability by measuring the number of transmitted qubits as a function of the number of semantic sentences

Summary

Summary

- Description on communication model beyond Shannon's symbol transmission to focus on meaning and goals.
- We proposed a novel approach by leveraging quantum communication channels and encoding techniques, like pre-trained large language models and graph neural networks
- We show the feasibility and performance evaluation of the quantum semantic communication evaluated on quantum simulator
- The time complexity analysis show the polynomial gain when quantum computation is applied
- The performance metric evaluations, including quantum semantic fidelity and F1 score, demonstrates that our approach remains resilient even in low signal-to-noise ratio environments, compared to SemComs, and traditional methods like Huffman encoding and 6-bit encoding which often fail to perform over AWGN channel.
- We demonstrated how distributed sensors generate semantic embedding that are fused into a single latent vector and mapped onto a quantum state for transmission. At the receiver, semantic fidelity is assessed using a quantum SWAP test between the received qubit and a goal-encoded reference state eliminating the need for full data recovery.
- This research envisions a transformative future at the intersection of semantics and quantum technologies, promising advancements in communication and computation.

Q&A ?

Thankyou!

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