GUEST EDITORIAL

Semantic Communications: Transmission Beyond Shannon


Geoffrey Ye Li


Yonina C. Eldar


Arash Behboodi


Guangyi Liu

The Shannon paradigm, or conventional communication, primarily focuses on how to accurately and effectively transmit symbols from the transmitter to the receiver. With the development of cellular communication systems, the transmission rate has been improved tens of thousands of times and is gradually approaching the Shannon limit. However, the existing communication paradigm is facing a serious bottleneck as a massive number of devices require wireless connectivity while spectrum resources are limited. In addition, due to the increasing deployment of intelligent IoT applications, e.g., human-computer interactions and machine-machine communications, semantic-agnostic communications are no longer ideal. Motivated by this, researchers have dedicated efforts for developing systems to process and exchange semantic information for more efficient communications. In contrast to the Shannon paradigm that focuses on correct reception of the transmitted packet regardless of its meaning, semantic communication is concerned with the issue of how to efficiently transmit and receive the desired meaning of the source content to the destination. By transmitting only the meaning or semantics of the source content, semantic communication holds the promise of making wireless networks significantly more energy-efficient, robust, and sustainable than ever before.

Despite the developments over the last seven decades, progress on semantic communications is still in its infancy due to lack of a general mathematical model for semantic representations. The new generation of wireless communication systems are expected to be empowered by intelligence in terms of signal processing, resource allocation, and decision making. Recent advancements on deep learning provide researchers with significant insights on developing semantic communication systems. As such, there are clear opportunities to exploit deep learning technologies to build semantic communication systems.

To further improve system efficiency and reduce the data traffic, semantic communication is a promising direction. This feature topic includes five articles that provide comprehensive tutorials, present novel solutions, and discuss technical challenges in the exciting area of semantic communications.

The article, entitled "Semantic Communications Based on Adaptive Generative Models and Information Bottleneck" by S. Barbarossa, D. Comminiello, E. Grassucci, F. Pezone, S. Sardellitti, and P. D. Lorenzo, demonstrates an interesting way to design semantic communication systems. The article finds many new freedoms that can be exploited for efficient semantic communications compared with its conventional counterpart. In particular, the article introduces a semantic communications approach based on three basic ideas: using topological space to capture semantics, adapting information bottleneck online according to wireless channel state, and adjusting transmission rate through a probabilistic generative model.

The article "Deep Joint Source-Channel Coding for Semantic Communications," by J.-L. Xu, T.-Y. Tung, B. Ai, W. Chen, Y.-X. Sun, and Deniz Gündüz, discusses joint source-channel coding (JSCC) to address strict latency, bandwidth, and power constraints in semantic communications. Even if JSCC has been well-investigated in conventional information theory, where separation theorem of source and channel coding has been proved under an ideal situation, recent research demonstrates that there still exists significant performance gain for JSCC in many practical situations, especially in semantic communications. This article introduces the design principles of machine learning based JSCC, demonstrates its benefits, and identifies some future research challenges.

The article "Is Semantic Communications Secure?" by Y. E. Sagduyu, T. Erpek, S. Ulukus, and A. Yener, investigates security issues in semantic communications. It models the semantic transceiver as an autoencoder followed by a task classifier. The autoencoder includes an encoder neural network at the transmitter and a decoder neural network at the receiver, which are jointly trained with the semantic task classifier to minimize a loss function consisting of reconstruction and semantic losses. From the article, the semantics of the transmitted information can be easily changed or distorted by either computer vision or wireless attaches. Therefore, it necessary to develop defense methods for the safe adoption of semantic communications.

The article "SemProtector: A Unified Framework for Semantic Protection in Deep Learning-Based Semantic Communication Systems," by X.-H. Liu, etc., proposes a unified framework to ensure security of semantic communications. Previous work in the related area focuses on the robustness of semantic communications through offline adversarial training while online semantic protection, even if more practical, is still largely underexplored. The SemProtector secures an online system with three hot-pluggable semantic protection modules to encrypt semantics, mitigate privacy risks, and calibrate distorted semantics, respectively. Through experiments to the two public datasets, the effectiveness of the SemProtecor is confirmed, which provides insights on how to reach the secrecy, privacy, and integrity in semantic communications.

The article "A Distributed Learning Architecture for Semantic Communication in Autonomous Driving Networks for Task Offloading" by G.-H. Zheng, Q. Ni, K. Navaie, H. Pervaiz, and C. Zarakovitis, addresses privacy issues in autonomous driving. Through analyzing autonomous driving networks (ADNs), the article indicates that it is impossible to directly update the ML-based semantic communication coder model due to many factors, such as mobility and privacy. Hence, it is very difficult to directly to use conventional machine-learning based framework for ADNs. This article develops a privacy-preserving personalized federated learning framework to address the unique challenge in ADNs, which is confirmed by extensive experimental results.

We would like to express our great gratitude to all authors for their submissions and anonymous reviewers for their insightful reviews and suggestions that have helped maintain the high quality of this feature topic. We are also grateful to Professors Xiaoming Tao and Zhijin Qin of Tsinghua University and Mr. Yiqun Ge of Huawei Technologies who have contributed this feature topic

Biographies

Geoffrey Ye Li (Geoffrey.Li@imperial.ac.uk) is currently a Chair Professor at Imperial College London, UK. He made fundamental contributions to OFDM for wireless communications and introduced deep learning to communications. Dr. Geoffrey Li was elected to IEEE Fellow and IET Fellow for his contributions to signal processing for wireless communications. He won 2024 IEEE Eric E. Sumner Award and several prestigious awards from IEEE Signal Processing, Vehicular Technology, and Communications Societies, including 2019 IEEE ComSoc Edwin Howard Armstrong Achievement Award.

Yonina Eldar [F] is a Professor in the Department of Math and Computer Science at the Weizmann Institute of Science, Rehovot, Israel, where she heads the center for Biomedical Engineering and Signal Processing. She is a member of the Israel Academy of Sciences and Humanities, an IEEE Fellow and a EURASIP Fellow. She has received many awards for excellence in research and teaching, including the IEEE Signal Processing Society Technical Achievement Award, the IEEE/AESS Fred Nathanson Memorial Radar Award, the IEEE Kiyo Tomiyasu Award, the Michael Bruno Memorial Award from the Rothschild Foundation, the Weizmann Prize for Exact Sciences, and the Wolf Foundation Krill Prize for Excellence in Scientific Research.

Arash Behboodi received Master in Philosophy from Université de Paris 1 in 2011 and Ph.D. degree from École Supérieure délectricité (now CentraleSupélec), Gif-sur-Yvette, France in 2012. Since 2019, he has been with Qualcomm AI research, where he is leading wireless machine learning research and works on fundamental machine learning research and design for wireless communication. His research activities include as well learning theory, inverse problems and compressed sensing, and information theory.

Guangyi Liu received his Ph.D. from Beijing University of Posts and Telecommunications and joined China Mobile since 2006, now he is the leading specialist and 6G director. He is vice chair of wireless access technology group of Chinese IMT-2030 promotion group. He has led the standardization and industrialization of 4G/5G in China Mobile. Now he is leading the 6G R&D. He has acted as the chair of spectrum working group and coordinator of 5G eMBB program in Global TD-LTE Initiative (GTI). He has been granted more than 150 patents, and authored more than 8 books and 150 papers.