Research Statement

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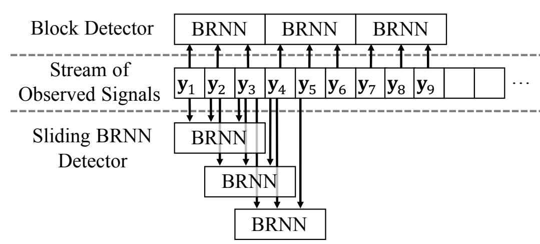
Communication system design has typically relied on the development of mathematical models that describe the underlying communication channel, which dictates the relationship between the transmitted and the received signals. However, in many systems, accurate channel models may not be known, or the models may not lend themselves to computationally efficient system design. In these scenarios, a completely new approach to communication system design and analysis is required. *My research focuses on developing novel data-driven techniques based on machine learning and statistics for design and analysis of communication systems in settings when accurate and simple models are not available.* This approach is inspired by the recent success of machine learning techniques in applications such as image classification, speech recognition, and machine translation. In my work, I have developed new tools and techniques for multiple aspects of communication system design using machine learning, including: novel detection algorithms that dynamically adapt to changing channel conditions, and neural-network based joint source-channel encoders and decoders that can be applied to text, images and video. I have also applied this approach in the emerging paradigm of molecular communication, where chemical signals are used for information transfer. Molecular communication channels are not well established, particularly for applications in bioengineering and medicine such as communication within the human body. My work has demonstrated that a machine learning approach to mitigating channel impairments, when models for such impairments are not accurate, leads to significantly better performance than conventional techniques. Application of machine learning techniques to communication system design also holds much promise across the protocol stack, for example, in traffic prediction, dynamic routing, and security.

1. Current Research

1.1 Machine Learning Approach to Design of Communication Systems

The field of machine learning has advanced significantly over the past few years because of deep neural network (NN) architectures. Machines can now classify images better than humans, and perform speech recognition and machine translation with high accuracy. This is achieved through a data driven approach, where deep NNs are trained directly on end-to-end data with limited modeling. Inspired by these results, in my work, I investigate how deep NNs can be used in communication system design, especially when the underlying models are imperfect or the design problem is complex. Some problems I have considered include: real-time sequence detection for continuous data streams with long memories; detection without any knowledge of the underlying channel models; and joint source-channel coding of data using deep NN encoders and decoders.

Sliding bidirectional recurrent neural network for real-time sequence detection. Recurrent neural networks (RNNs) are typically used in machine learning tasks that work with sequential data such as natural language processing and speech processing. One of the drawbacks of RNNs is that they are feedforward, and the estimate of the current word or sound is only affected by previously observed words or sounds. However, in systems with memory, future observations can affect the current estimate of words or sounds. To overcome this issue bidirectional RNNs (BRNNs) are used to jointly estimate sequences in one block. This technique cannot be applied to continuous real-time estimation of data streams. To solve this problem, I have developed sliding BRNNs, where the block length of the BRNN increases to a maximum length and then slides across the incoming data stream [1]. The outputs of the sliding BRNN are then combined using a dynamic programming approach, where the estimate of the previously observed data is constantly refined. The computational complexity of this approach increases linearly with memory length, making it suitable for applications with long memory. I have demonstrated that sliding BRNNs can achieve a detection performance that is close to the optimal Viterbi detector with significantly lower computational complexity. I have filed a **provisional patent on the devised algorithm through the Stanford Office of Technology Licensing [2]**.



Detection in communication systems without channel models. In some systems, such as chemical communication with multiple chemicals that react with each other, the underlying channel models are unknown and complex. Moreover, even when the channel models are known, many detection algorithms rely on the instantaneous channel state information (CSI), i.e., the instantaneous parameters of the model, for detection. Therefore, the instantaneous CSI needs to be estimated by transmitting and receiving a predesigned pilot sequence. However, this estimation process entails overhead, which decreases the data transmission rate. Moreover, the accuracy of the estimation may also affect the performance of the detection algorithm. I have investigated how a data driven approach can be used to train NN detectors directly from simulations, experimental measurements, or field measurements, without the underlying channel models [3,4]. Moreover, I have shown that if the training dataset is rich enough, with sample transmissions under various channel conditions, the trained NN detector performs well in changing channel conditions without the need to estimate CSI or the performance degradation that results when such estimates are inaccurate.

Joint source-channel coding using neural networks. In digital communications, data transmission typically entails source coding and channel coding. In source coding the data is mapped to a sequence of symbols where the sequence length is optimized. In channel coding, redundant symbols are systematically added to this sequence to detect or correct the errors that may be introduced during data transfer. The separation theorem states that source and channel codes can be designed separately, with no loss in optimality for certain classes of communication channels. However, this optimality of separation assumes no constraint on the complexity of the channel code design. Therefore, many communication systems may benefit from designing the source and channel codes jointly. I have developed a novel joint source-channel coding scheme for text data transmitted over erasure channels using a NN encoder and a NN decoder [5]. In this system, instead of recovering the exact sentence at the receiver, the goal is to recover the semantic information such as facts or imperatives of the sentence. For example, the phrase "the car stopped" and "the automobile stopped" convey the same information. I have shown that the NN encoder and decoder that I have proposed outperforms the traditional separate source and channel code design in terms of word error rate (WER) when the bit budget per sentence encoding is low. Moreover, in many cases, although some words may be replaced, dropped, or added to the sentence by the NN decoder, the semantic information in the sentence is generally preserved.

1.2 Design and Analysis of Molecular Communication Systems

In molecular communication, the transmitter releases chemicals or molecules and encodes information on some property of these signals, such as their type, timing, or concentration. The signal then propagates through the medium between the transmitter and the receiver, via means such as diffusion or convection, until it arrives at the receiver where the signal is detected and the information is decoded. This is a rapidly growing new field for networking devices with dimensions much less than a millimeter [6]. Molecular communication now has its own IEEE transactions journal[1] and has been named one of the "Ten Communications Technology Trends for 2017" by IEEE ComSoc[2]. One of the main motivations behind this technology is in-body communication. For example, bio-sensors, such as synthetic biological devices, can constantly monitor an individual for disease biomarkers and chemically transmit their measurements to an implanted device on or under the skin, enabling real-time health monitoring systems. Some of my past and current research has been on design and analysis of molecular communication systems using a model-based approach. I highlight these contributions below.

Capacity analysis and design of molecular channels. The Shannon capacity of a communication channel characterizes the maximum theoretical achievable data rates for that channel. Understanding this theoretical limit provides an upper bound on performance as well as intuition that is useful for system design. I have derived these theoretical limits for molecular timing channels where information is encoded in the time-of-release of particles at the transmitter and is decoded from the time-of-arrivals at the receiver [2-4]. Since particles propagate randomly, they may arrive out-of-order and some of them may never arrive due to degrading effects of the environment. Therefore, the channel will have both memory and erasures. For a channel model where information particles degrade after some arbitrary time and rely on diffusive transport, I showed that a data rate of up to 2 bits per second is theoretically possible. Moreover, I have shown that when the transmitter releases multiple particles during each symbol transmission, the capacity increases poly-logarithmically with the number of particles used. Another technique for modulating information on chemical signals is using the number of particles released by the transmitter. The information is then decoded from the number of particles that arrive at the receiver during the symbol duration. In this channel, information particles may never arrive or may interfere with future transmissions because of degradation and random propagation. I have devised a model for this channel where the information particles have an arbitrary lifetime, derived the Shannon capacity for this channel, and showed that in many systems with diffusion transport of the particles, binary on-off-keying is the optimal transmission strategy [5]. I also demonstrated that this optimal transmission strategy does not depend on the type of particles. Another aspect of my research has focused on receiver design, where I have derived the optimal sequence detector for timing and particle intensity modulation schemes [14-15]. I have also developed computationally efficient heuristic algorithms and via simulations demonstrated that these heuristic schemes achieve performances close to that of the optimal detectors for both systems.

Optimal design for molecular communication in bio-chips. In communication systems, optimal design improves the performance of the system and ensures that the best possible data rate and reliability is achieved. One aspect of my research has focused on optimal design for molecular communication in bio-chips, where components within a chip, such as a DNA storage unit and a molecular processing unit, are connected by chemical signaling. The bio-chips use chemical and molecular properties and interactions for storage and processing of information. They are different from silicon-based chips that use electrical properties and electrical signals. In bio-chips, using molecular communication is simpler than converting chemical properties into electric signals and then converting them back to chemical properties. I have used information theory, modeling, and optimization to provide design guidelines for optimal placement of components on the bio-chip such that the data rate between the components are maximized [11-13]. I showed that when the proposed optimal design is used, the information rate is improved by almost an order of magnitude compared to the standard design.

Experimental demonstrators for molecular communication. Since the field of molecular communication is still in its infancy, experimentally validated standardized models do not yet exist. Therefore, some of my research has focused on building experimental demonstrators for validating and testing different models and designs. I have built the world's first molecular communication platform [16], and developed the mathematical channel models for the platform [17]. The goal of this system was to reliably transmit short

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1 IEEE Transactions on Molecular, Biological and Multi-scale Communications: http://www.comsoc.org/tmbmc

2 http://www.comsoc.org/blog/top-10-communications-technology-trends-2017

messages over a distance of a few meters. This system used an electronically controlled spray as the transmitter, a metal oxide sensor that detects the concentration of alcohol at the receiver, and aerosolized alcohol as the information-carrying chemical. This work attracted media coverage by The Economist, The Royal Society of Chemistry, and the Wall Street Journal, as well as other national and local newspapers. This work was selected as a **finalist for the 2014 Bell Labs Prize** and won the **Second Prize for the 2014 IEEE ComSoc Student Competition**. This initial demonstrator has evolved to incorporate two advanced communication techniques: MIMO strategies, and communication using multiple reactive chemicals. In particular, my collaborators and I have incorporated techniques from MIMO radio communication into my platform using two alcohol transmitters and two receivers [18]. This demonstration, which led to an increased data rate, won the **Best Demo award at the IEEE-INFOCOM'2015** conference. I have also designed and built a new platform for multi-chemical communication in vessel-like environments [3]. This new platform has two attractive features. First, it simulates an environment that resembles a vein in the body. Second, it uses multiple reactive chemicals to create both constructive and destructive signal superposition. This can be used to reduce the intersymbol interference (ISI) at the receiver or to create orthogonal signals. I have demonstrated that this ISI mitigation can improve the data rate by up to an order of magnitude using some of the NN detectors I have developed.

2. Future Research Plans

Moving forward, I intend to continue to explore how techniques from deep learning more broadly can be used to improve the design of communication systems across all network layers. I also plan to further investigate how to design molecular systems for in-body communication and for on-chip communications. Below I highlight several directions I intend to pursue.

Communication link and network design using deep learning and artificial intelligence. Despite the disruptive effect deep learning has had in many applications such as natural language processing and image processing, their use in designing communication networks has not been studied extensively. This motivates my interest in further exploration of this topic along the following areas.

- *Adaptive NN detection algorithms.* In many communication systems, the channel conditions change with time. In my prior work, I have demonstrated that it is possible to train NN detectors that achieve good performance under various channel conditions. I propose that these results can be further improved by using reinforcement learning and channel coding. In this setting, channel codes are used to track and correct some of the errors in the detection process. Instances where an error is detected and corrected are used to refine the parameters of the detector using reinforcement learning. Such a detector would dynamically adapt to changing channel conditions, and would potentially improve performance over current techniques that use periodic training.
- *Joint source-channel coding for images and video.* Some recent work on NN encoder and decoder architectures have shown impressive results in image and video compression. Moreover, in many applications instead of recovering the exact transmitted data, we are interested in recovering some information of interest from the data. For image and video data, the information of interest could be the main object of interest in an image rather than the entire image, and any image that preserves this information is considered as an error free output by the decoder. I plan to extend the joint source-channel coding design that I previously applied to text using NNs to image and video data. Since the vast majority of Internet traffic is video, if the average number of bits per frame is reduced, there can be a considerable improvement in data traffic.
- *Data-driven protocol design for transport and network layer.* In communication networks, a routing strategy specifies how the traffic is directed from each source to each destination node in the network. A demand matrix specifies the traffic demand between each source and each destination. The goal of the routing algorithm is to present a routing strategy that minimizes an optimization objective (e.g. network congestion). Given the network topology and a demand matrix, optimal routing configurations can be efficiently computed for a broad range of optimization objectives. However, in practice, the demand matrix or the network topology may be unknown and can change over time. Traditional routing schemes address this challenge in two ways: 1) optimizing routing with respect to past traffic conditions instead of current conditions; and 2) optimizing static routing configurations for a range of feasible traffic scenarios. I propose a third approach based on a data-driven protocol design using machine learning. First, I plan to develop NN architectures for predicting future demand and topology from past data using supervised learning. These estimates are then employed to compute the optimal routing strategy. Second, I intend to develop algorithms based on reinforcement learning to further refine these results.
- *Engineering the training dataset.* It is well known in machine learning that the quality of the dataset can have a tremendous effect on the training and performance of NNs. I have also observed this effect in my work on NN detection in communication channels with unknown models. I plan to study this area further and understand what datasets result in the best performance after training ends and real data is transmitted. I intend to investigate if information theoretic measures such as entropy and mutual information can be used to characterize traits in the training dataset that would have the largest effect on the robustness of the trained NNs used in communication systems.
- *User verification using radio fingerprints.* Radio transmitters are naturally imperfect devices due to the tolerances in manufacturing of the analog electronics. The imperfections result in a "radio fingerprint" for each transmitting device that can uniquely identify the device. The communications security literature has many examples of the radio fingerprint concept. The typical research on this topic centers around a few nominally identical transmitters of a single protocol type and studies their transmit signals in order to hand-engineer features that discriminate the individual transmitters. While successful as proof of concept demonstrations, hand-

engineered feature-discriminators have not been shown to support the number of devices expected in larger networks. In this scenario, since signals can have large dimensions, and there are many nodes, I intend to use deep learning to extract the most relevant set of features for user identification from radio signals.

Design and implementation of molecular communication systems. Molecular communication, is still in its infancy and there are many open problems in this area. I plan to continue my research through system design, capacity analysis, and implementation.

- *System design and capacity analysis.* I intend to investigate the design of both point-to-point and multiuser molecular communication systems. Point-to-point links suffer from severe ISI, and I plan to develop novel ISI mitigation schemes using chemical reactions. In multiuser environments, one area I intend to investigate are fundamental capacity limits, which is still an open problem. Another area is multiuser access where I aim to explore if the constructive and destructive chemical interactions can be exploited to develop a set of unique codes that can be assigned to each user such that the signals do not interfere with each other at the receiver. This would be similar to code-division multiple access (CDMA) in wireless communications. I also plan to investigate how higher layer network protocols such as routing algorithms can be implemented in molecular communications with multiple nodes.

- *Experimental platforms*. In the future, I intend to develop new experimental platforms that simulate a real in-body molecular communication environment. In particular, my goal is to build an artificial network of veins and arteries, which will be developed as an extension of my multi-chemical in-vessel platform. Using the platform, one can simulate a device injecting different chemicals such as drugs, sugars, or proteins into the blood stream. The resulting chemical signal propagation can be measured by different detectors such as a glucose detector. I intend to improve the design of this platform iteratively, making the system more realistic with each iteration. Through collaborations with biologists and bioengineers I plan to eventually demonstrate in-body chemical communication *in-vivo*.

A remarkable technological trend is now taking place under the name of *machine learning*, which has revolutionized many fields including natural language processing and computer vision. This phenomenon presents numerous exciting opportunities for my endeavor in further developing this technology to improve the design of communication networks. Considering the interdisciplinary nature of some of my research, I have collaborated broadly with a wide range of experts in different engineering and science disciplines in my previous work, and I look forward to forging new collaborations to carry out my future research interests as described above.

References

[1] N. Farsad, and A. Goldsmith, “Sliding Bidirectional Recurrent Neural Networks for Sequence Detection in Communication Systems,” *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, submitted, 2018.

[2] N. Farsad, and A. Goldsmith, “Systems and methods for transmitting data using machine learning classification,” U.S. Provisional Patent 62/458,936, Feb. 14, 2017.

[3] N. Farsad, D. Pan, and A. Goldsmith, “A Novel Experimental Platform for In-Vessel Multi-Chemical Molecular Communications,” *IEEE Global Communications Conference (GLOBECOM)*, accepted, 2017.

[4] N. Farsad, and A. Goldsmith, “Neural Network Detectors for Sequence Detection in Communication Systems,” *IEEE Transactions on Signal Processing*, submitted, 2017.

[5] N. Farsad, M. Rao, and A. Goldsmith, “Deep Learning for Joint Source-Channel Coding of Text,” *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, submitted, 2018.

[6] N. Farsad et al., “A comprehensive survey of recent advancements in molecular communication,” *IEEE Communications Surveys & Tutorials,* vol. 18, no. 3, pp. 1887–1919, 2016.

[7] N. Farsad, Y. Murin, A. W. Eckford, and A. Goldsmith, “Capacity Limits of Diffusion- Based Molecular Timing Channels,” *IEEE Transactions on Information Theory*, submitted, 2017.

[8] N. Farsad, Y. Murin, M. Rao, and A. Goldsmith, “On the Capacity of Diffusion-Based Molecular Timing Channels with Diversity,” *Asilomar Conference on Signals, Systems, and Computers*, 2016.

[9] N. Farsad, Y. Murin, A. W. Eckford, and A. Goldsmith, “On the Capacity of Diffusion- Based Molecular Timing Channels,” *IEEE International Symposium on Information Theory (ISIT)*, 2016.

[10] N. Farsad, C. Rose, M. Medard, and A. Goldsmith, “Capacity of Molecular Channels with Imperfect Particle-Intensity Modulation and Detection,” *IEEE International Symposium on Information Theory (ISIT)*, 2017.

[11] N. Farsad, A. W. Eckford, S. Hiyama, and Y. Moritani, “On-Chip Molecular Communication: Analysis and Design,” *IEEE Transactions on NanoBioscience*, vol. 11, no. 3, pp. 304–314, 2012.

[12] N. Farsad, A. W. Eckford, and S. Hiyama, “A Markov Chain Channel Model for Active Transport Molecular Communication,” *IEEE Transactions on Signal Processing*, vol. 62, no. 9, pp. 2424–2436, 2014.

[13] N. Farsad, A. W. Eckford, and S. Hiyama, “Design and Optimizing of On-Chip Kinesin Substrates for Molecular Communication,” *IEEE Transactions on Nanotechnology*, vol. 14, no. 4, pp. 699–708, 2015.

[14] Y. Murin, N. Farsad, M. Chowdhurya, and A. Goldsmith, “Time-Slotted Transmission over Molecular Timing Channels,” *Elsevier Nano Communication Networks*, vol. 12, pp. 12–24, 2017.

[15] V. Jamali, N. Farsad, R. Schober, and A. Goldsmith, “Non-Coherent Detection for Diffusive Molecular Communications,” *IEEE Transactions on Communications*, submitted (minor revisions first round), 2017.

[16] N. Farsad, W. Guo, and A. W. Eckford, “Tabletop Molecular Communication: Text Messages Through Chemical Signals,” *PLOS ONE*, vol. 8, no. 12, 2013.

[17] N. Farsad, N.-R. Kim, A. W. Eckford, and C.-B. Chae, “Channel and Noise Models for Nonlinear Molecular Communication Systems,” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 12, pp. 2392–2401, 2014.

[18] B. Koo, C. Lee, H. B. Yilmaz, N. Farsad, A. W. Eckford, and C.-B. Chae “Molecular MIMO: From Theory to Prototype,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 3, pp. 600–614, 2016.