Research Statement

Animashree Anandkumar

My research interests are in the broad area of signal processing, communications, networking, and information theory. I have worked on distributed inference of graphical models, routing and random-access schemes, error-exponent analysis, and queueing models. My work has been interdisciplinary, borrowing tools from areas such as combinatorial optimization, large deviations, and probabilistic methods such as random-graph theory. In this statement, I will first briefly describe my past and current research activities.

1 Research Activities

We are living in an increasingly networked world with networks of varying scales: the nodes in the network can comprise of tiny devices, our personal gadgets, or even our friends. The nature of links is also varied; they can be wireless, wire-line, or social links. There is rich interaction and information flow between these networks - for instance, between the computer and the social networks. So far, these different networks have been mostly studied as independent entities.

Another feature of these networks is the massive scale of the data they generate. Analysis of such large data sets requires scalable algorithms whose computational complexity does not grow with data. Moreover, since data is generated at a large number of nodes, the communication requirements of an algorithm is a key parameter. Depending on the application, algorithms need to undertake distributed computations at various nodes for communication requirements to be scalable in the data size and in the number of nodes in the network. Below, I present my thesis research on scalable algorithms for distributed inference, based on the works in [1–13].

1.1 Distributed Inference of Dependency Graph Models

Dependency graph is an effective model for relationships between nodes in a network based on some attribute, and needs to be inferred from the data generated by the nodes. To this end, nodes need to communicate their data to more powerful decision nodes referred to as the *fusion centers*. However, such communications entail costs in the form of energy, delay, and bandwidth requirements.

If the nodes were to communicate all their raw data to the fusion centers, then such a scheme has a high communication cost, and is not scalable in the network size. However, if the end goal is inference, there is no need to communicate all the raw data; instead, we should compute and communicate the *sufficient statistic*, a function of the raw data, which ensures that there is no loss in inference performance. At the same time, the sufficient statistic has dimensionality reduction resulting in savings of communication costs. For a dependency graph model, the sufficient statistic has a compact form based on local dependency graph properties. In [1], we propose a scheme for distributed computation of the sufficient statistic by exploiting the dependency graph structure.

Our scheme is scalable - it has strictly bounded average communication costs, even as the network grows, for a wide range of dependency graph models. Intuitively, when the dependency graph has only short-range edges between nearby nodes, the computation of the sufficient statistic can be undertaken locally with low communication costs. We provide a precise definition of such local dependency graphs based the concept of graph *stabilization* using the recent results on random geometric graphs. Such local dependency graphs occur in many scenarios - for example, the dependency between the location-based search queries and internet users; users near a particular location are more likely to query about that location than the ones further away. Another example is a sensor network measuring temperature of a field where nearby sensors tend to record similar temperatures.

We also provide a closed-form expression for average communication cost for inference under our scheme, and it has a nice representation in terms of the dependency graph, communication-cost function, and node placement. We use the expression to design efficient node placement strategies with low communication costs in [2]. We also address the related issue of selecting informative nodes for inference and designing optimal fusion schemes in [4–7] to further reduce the communication costs.

1.2 Medium-Access Control for Distributed Inference

We consider medium-access control (MAC) schemes for communication between the nodes in a network and the fusion center in [9–11]; the end goal is inference about a common underlying phenomenon measured by the nodes. Traditionally, MAC schemes allocate transmission from different nodes to orthogonal channels (such as in time or frequency) to avoid interference. Instead, we propose a MAC scheme where nodes may interfere with one another, yet achieve good inference accuracy in the end. We allocate orthogonal channels to data levels: all nodes reaching the same local decision use the same orthogonal channel to transmit, if they decide to do so.

The extent to which interference aids inference depends on the nature of the multiple-access channel. If the channel adds energies of interfering transmissions efficiently, then simultaneous transmissions are more likely in our scheme. On the other hand, if the channel cancels energies of interfering transmissions, then transmissions on independent orthogonal channels are more likely to avoid any interference. Hence, our scheme adapts medium-access control based on the channel conditions to maximize inference performance, and it outperforms the classical orthogonal transmission scheme in terms of inference accuracy and bandwidth efficiency under the same energy budget.

1.3 Probabilistic Transaction Monitoring in Distributed Systems

My internships at IBM Watson Research resulted in a new line of work [**?**, 12] on probabilistic monitoring of transactions in distributed systems. Current enterprise systems are made up of a complex array of machines, and process a large number of transactions simultaneously. We have all experienced slow online credit-card transactions and other process glitches. Such problems can take days or even weeks to debug manually. Instead, deploying an automated continuous monitoring of the transactions makes debugging a cake walk. However, current systems provide only limited information in the form of records of events and time-stamps. In [12], we employ the statistical notion of *maximum-likelihood* (ML) tracking of transactions using the data-records. We analyze the ML-rule and provide fundamental limits on its performance. Our work was presented at ACM Sigmetrics '08, a highly selective conference in the area of performance analysis.

The above problem is extended in [13], where we consider the possibility of retrofitting monitoring instrumentation. Such an exercise provides precise monitoring but is expensive to deploy throughout the network. Under a budget constraint, we propose optimal selective instrumentation strategy which identifies monitoring bottlenecks where such retrofitting is most useful for monitoring. We have also filed an invention disclosure regarding our selective instrumentation strategies.

References

[1] A. Anandkumar, J. Yukich, L. Tong, and A. Swami, "Energy Scaling Laws for Distributed Inference in Random Networks," *IEEE J. Selec. Area Comm.*, Sept. 2009.

[2] A. Anandkumar, L. Tong, and A. Swami, "Optimal Node Density for Detection in Energy Constrained Random Networks," *IEEE Tran. Signal Proc.*, vol. 56, pp. 5232–5245, Oct. 2008.

[3] A. Anandkumar, L. Tong, and A. Swami, "Detection of Gauss-Markov Random Fields with Nearest-neighbor Dependency," *IEEE Tran. Information Theory*, vol. 55, pp. 816–827, Feb. 2009.

[4] A. Anandkumar, M. Wang, L. Tong, and A. Swami, "Prize-Collecting Data Fusion for Cost-Performance Tradeoff in Distributed Inference," in *Proc. of IEEE INFOCOM*, (Rio De Janeiro, Brazil), April 2009. **Acceptance Rate 20%**.

[5] A. Anandkumar, L. Tong, A. Swami, and A. Ephremides, "Cost-Performance Tradeoff in Multi-hop Aggregation for Statistical Inference," in *Proc. of IEEE ISIT*, (Toronto, Canada), July 2008.

[6] A. Anandkumar, L. Tong, A. Swami, and A. Ephremides, "Minimum Cost Data Aggregation with Localized Processing for Statistical Inference," in *Proc. of INFOCOM*, (Phoenix, USA), pp. 780–788, April 2008. **Acceptance Rate 20%**.

[7] A. Anandkumar, A. Ephremides, A. Swami, and L. Tong, "Routing for Statistical Inference in Sensor Networks," in *Handbook on Array Processing and Sensor Networks* (S. Haykin and R. Liu, eds.), ch. 23, John Wiley & Sons, 2009.

[8] A. Anandkumar and L. Tong, "Inference in Networks," in *Foundation and Trends in Networking*, in preparation: Now Publishers, 2009.

[9] A. Anandkumar and L. Tong, "Type-Based Random Access for Distributed Detection over Multiaccess Fading Channels," *IEEE Tran. Signal Proc.*, vol. 55, pp. 5032–5043, Oct. 2007. **IEEE Signal Processing Society 2008 Young Author Best Paper Award**.

[10] A. Anandkumar, L. Tong, and A. Swami, "Distributed estimation via random access," *Information Theory, IEEE Transactions on*, vol. 54, pp. 3175–3181, July 2008.

[11] A. Anandkumar and L. Tong, "A Large Deviation Analysis of Detection over Multi-Access Channels with Random Number of Sensors," in *Proc. of ICASSP'06*, vol. IV, (Toulouse, France), pp. 1097–1101, May 2006. **Best Paper Award**.

[12] A. Anandkumar, C. Bisdikian, and D. Agrawal, "Tracking in a Spaghetti Bowl: Monitoring Transactions Using Footprints," in *Proc. ACM Intl. Conf. on Measurement & Modeling of Computer Systems (Sigmetrics)*, (Annapolis, Maryland, USA), June 2008. **Acceptance Rate 18%**.

[13] A. Anandkumar, C. Bisdikian, T. He, and D. Agrawal, "Designing A Fine Tooth Comb Frugally: Selectively Retrofitting Monitoring in Distributed Systems," (Seattle, USA), June 2009. Workshop on Mathematical Performance Modeling and Analysis (MAMA).