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Final Report for

W911NF1410368: Exploiting the Multi-Channel Advantage for Wireless Ad Hoc Networks: Achieving both High Throughput and Low Delay with Low-Complexity Control

In this project, we aim to develop control strategies for ad hoc wireless networks that, for the first time in the literature, will simultaneously optimize along three critical dimensions of performance: delay; throughput; and complexity. In particularly, our goal is to develop low-complexity and distributed algorithms that can simultaneously achieve both provably-high throughput and provably-low delay.

The project presents the first comprehensive study for multi-channel advantage in large-scale wireless ad hoc networks. In particular, we will (i) develop implementable algorithms and protocols that benefit practical systems with either a single physical channel or multiple physical channels; (ii) design solutions that can quickly adapt to highly-dynamic and mobile environments; (iii) extend the multi-channel advantage to systems with multi-hop traffic and dynamic routing to provably achieve end-to-end high throughput and low-delay with low-complexity operations; (iv) develop algorithms that can fully realize the potential gain of advanced physical-layer mechanisms (such as MIMO and adaptive modulation/coding) with low-complexity control.

Accomplishments:

- We developed low complexity sample path optimal algorithms for wireless networks under the tree topology and the K-hop interference model. Fully characterized the existence of causal sample-path optimal scheduling policies in these networks, i.e., we wish to find a policy such that at each time slot, for any traffic arrival pattern, the sum of the queue lengths of all the nodes is minimum among all policies.
- We developed the first scheduling scheme that performs provably well under fading channels and is amenable to implement in a distributed manner. The scheme is provably efficient under fading environments, requires only local information, and has a low complexity that grows logarithmically with the network size (provided that the conflict graph has bounded maximum vertex degree).
- We developed application-level opportunistic scheduling algorithms that significantly improve spectrum efficiency by intelligently scheduling delay-tolerant applications, while at the same time meeting users' soft/probabilistic deadline constraints. The developed methodology uses a novel asymptotic approach that exploits the largeness of the network to alleviate the exponentially-high complexity typically associated with such problems with fading channels and deadline constraints. The developed algorithms incur low complexity, and are provably asymptotically optimal under very general settings.
- We studied concurrent channel probing and data transmission in full-duplex MIMO networks. Massive MIMO is a promising technique to scale the network capacity with the number of antennas. Traditionally, with the number of antennas/users increasing, the overhead of channel probing becomes substantial, which could greatly limit the time left for data transmission within the channel coherence time. To avoid the large overhead of channel probing, we were trying to break the boundary between channel probing and data transmission. When a user sends the probing signal to the transmitter via uplink, the transmitter with full-duplex capability could send downlink traffic to a set of users with known channel states at the same time. In our work, we proposed the first

concurrent channel probing and data transmission scheme in full-duplex MIMO networks and developed scheduling algorithms which achieve throughput optimality or near-optimal throughput performance at a low complexity.

We considered the downlink phase of a single cell network with one Base Station and a set of N users. The BS has a large number of antennas and full-duplex capability. N users are divided into I groups, where users from different groups have no mutual interference. In this work, we designed scheduling algorithms that decide when the uplink and downlink should be turned on, and which packets to be transmitted on both links, based on the available channel state knowledge and the queue backlog information. Our goal is to develop such scheduling algorithm to achieve provably good throughput performance at a low complexity.

We first proposed an algorithm which stabilizes any arrival vector within the capacity region (i.e., throughput optimality) with O(NI) iterations. To reduce the complexity, we further developed a low complexity greedy policy which utilizes queue-length as a decision metric. The greedy policy only takes O(N) iterations and it has been proved that this policy achieves at least ½ of the capacity region and its stability region is strictly larger than the capacity region of half-duplex mode when there are at least two groups. Furthermore, we used simulations to validate the insight from the theoretical analysis.

- We studied the impact of limited Channel State Information on Massive MIMO network performance. In recent years, there have been significant efforts on the research and development of Massive MIMO (M-MIMO) technologies at the physical layer. So far, however, the understanding of how M-MIMO could affect the performance of network control and optimization algorithms remains rather limited. In this work, we focus on analyzing the performance of the queue-length-based joint congestion control and scheduling framework (QCS) over M-MIMO cellular networks with limited channel state information (CSI).

  In this work, we accept the reality that CSI inaccuracy is unavoidable and we do not require full CSI at the M-MIMO BS. Instead, we assume that the CSI at the BS is limited and accurate only to a certain degree. Such limited CSI can be obtained by a small amount of feedback from each mobile device using a limited number of bits, say B, to approximately represent its channel instantiation. Alternatively, the BS could use B bits to approximately represent the downlink CSI based on the channel reciprocity assumption. The key question that we are interested in studying is how does the B-bit limited CSI affect the performance of the queue-length-based joint congestion control and scheduling framework.

  Our contributions in this work are two-fold: i) We characterize the scaling performance of the queue-lengths and show that there exists a phase transitioning phenomenon in the steady state queue-length deviation respect to the CSI quality (reflected in the number of bits B that represent CSI); and ii) We characterize the congestion control rate scaling performance and show that there also exists a phase transitioning phenomenon in steady-state congestion control rate deviation respect to the CSI quality. Collectively, the findings in this paper advance our understanding of the trade-offs between delay, throughput, and the accuracy/complexity of CSI acquisition in M-MIMO cellular network systems. Our work also establishes a unifying theoretical framework as well as practical design guidelines to enable the development of effective channel quantization schemes for M-MIMO networks.

- We develop new algorithms towards a practical large multicast deployment. One of the major reasons why multicast has not seen large scale deployments in wireless networks is that existing techniques tradeoff performance for overhead. A long-standing open problem has been to achieve reliable multicast with low delay and low feedback overhead. For example, for a multicast group of n receivers, existing techniques either achieve high throughput at the cost of prohibitively large (e.g., O(n)) feedback overhead, or achieve low feedback overhead but without either optimal or near-optimal throughput guarantees. Our goal is to overcome these difficulties to provide low-delay, low-overhead multicast that achieves high throughput at the same time.

  We hope to resolve the long-standing open problem of how to simultaneously achieve O(1) delay, throughput optimality, with using only O(1) feedback for large multicast communications. We hope to also leverage the multi-antenna capability of wireless networks in order to get significant additional gains.

  In our Mobihoc 2016 work, we have developed a novel anonymous-query based rate control, which approaches the optimal throughput with a constant feedback overhead independent of the number of receivers. In addition to our theoretical results, through implementation on a software-defined ratio platform, we show that the anonymous-query based algorithm achieves low overhead and robustness in practice.

- We studied how to exploit multiple degrees of freedom in MIMO OFDM systems to lower delay. There have been recent attempts to develop scheduling schemes for downlink transmission in a multi-channel (e.g., OFDM-based) cellular network. These works have been quite promising in that they have developed low-complexity index scheduling policies that are delay-optimal (in a large deviation rate-function sense). However, these policies require that the channel is ON or OFF in each time-slot with a fixed probability (i.e., there is no memory in the system), while the reality is that due to channel fading and doppler shift, channels are often time-correlated in these cellular systems. Thus, an important open question is whether one can find simple index scheduling policies that are delay-optimal even when the channels are time-correlated.

  Our goal is to develop simple index based scheduling policies that can exploit the multiple degrees of freedom provided by multiple channel OFDM type of systems, as well as the large number of antennas that a BS can use for downlink communications in order to provide throughput and delay optimality. Unlike recent exciting but limited works that have focused on channel models with no memory, we would like to design our solutions that can work well under arbitrary channel correlation models.

  We show that for certain classes of correlated channels, the class of oldest packets first (OPF) policies that give a higher priority to packets with a large delay are delay optimal (from the point of view of optimizing the large deviation rate function) as long as the number of channels is large. Further, we provide a set of very simple index type of OPF policies that can be implemented in practice with low complexity, and also achieve throughput optimality.

- We study how to cluster Remote Radio Heads (RRHs) into Virtual Base-Stations (VBSs) in a Cloud-based Radio Access Network. While forming a VBS cluster improve the performance to cell-edge users, it increases the interference footprint and may reduce overall spatial reuse. Thus, the decision to cluster or not should be carefully made based on topology and load patterns. Existing studies in the literature either incur high complexity or impose restrictions on the clustering patterns. Instead, we are interested in developing fast and low-complexity algorithms without such restrictions.

Specifically, we develop a Gibbs-sampling based algorithms that can find the desirable global VBS configuration from an arbitrarily given set of allowable VBS configurations. While Gibbs-sampling has been used to solve other wireless control problems, its application to VBS clustering faces new challenges both due to the difficulty in estimating the quality of a VBS configuration under rapid channel variations, and due to a new global coupling effect. We leverage Random Matrix Theory to develop a method that can quickly estimate the quality of a VBS configuration based only on average channel statistics. Further, we use perturbation analysis to develop a distributed approximation of the Gibbs sampler to circumvent the global coupling effect, which then allows different parts of the network to search for better VBS configurations in parallel. Our numerical results demonstrate how the proposed algorithm can not only improve edge-user performance, but also maintain high overall system utility.

- We develop full-duplex techniques that enables simultaneous bidirectional in-band cut-through transmissions between two far apart nodes. Multi-antennas can enable full duplex communication that can potentially double the channel capacity and achieve lower delays by empowering two radios to simultaneously transmit in the same frequency band. However, full duplex is only available between two adjacent nodes within the communication range. In recent work, we develop the first bi-directional full duplex technique (BiPass) to break this limitation. With the help of full duplex capable relays, we enable simultaneous bidirectional in-band cut-through transmissions between two far apart nodes, so they can do full duplex communications as if they were within each other's transmission range. To design such a system, we analyze interference patterns and propose a loop-back interference cancellation strategy. We identify the power amplification problem at relay nodes and develop an algorithm to solve it. We also develop a routing algorithm, an opportunistic forwarding scheme, and a real-time feedback strategy to leverage this system in ad-hoc networks. To evaluate the real world performance of BiPass, we build a prototype and conduct experiments using software defined radios. We show that BiPass can achieve 1.6x median throughput gain over state-of-the-art one-way cut-through systems, and 4.09x gain over the decode-and-forward scheme. Our simulations further reveal that even when the data traffic is not bidirectional, BiPass has 1.36x throughput gain and 47% delay reduction over one-way cut-through systems in large networks.

- We investigate competitive online algorithms for online convex optimization (OCO) problems with linear in-stage costs, switching costs and ramp constraints. This can be useful framework to deal with decisions in large networks with uncertainty (e.g., uncertain future traffic demand) and hard constraints (e.g., switching cost in order to change radio channels in wireless systems or to migrate to different servers in data-centers). While OCO problems have been extensively studied in the literature, there are limited results on the corresponding online solutions that can attain small competitive ratios. We first develop a powerful computational framework that can compute an optimized competitive ratio based on the class of affine policies. Our computational framework utilizes affine policies to obtain low-complexity decisions. Further, it can handle a fairly general class of costs and constraints. Compared to other competitive results in the literature, a key feature of our proposed approach is that it can handle scenarios where infeasibility may arise due to hard feasibility constraints. Second, we design a robustification procedure to produce an online algorithm that can attain good performance for both average-case and worst-case inputs. We conduct a case study on Network Functions Virtualization (NFV) orchestration and scaling, and we demonstrate that the proposed methodology can attain significantly lower competitive ratios that state-of-art solutions based on Receding Horizon Control.

Products:

Journals:

1. Y. Sun, E. Uysal-Biyikoglu, R. D. Yates, C. E. Koksal, and N. B. Shroff, “Update or Wait: How to Keep Your Data Fresh,” IEEE Trans. on Information Theory, accepted for publication.
2. J. Liu, A. Eryilmaz,, N. B. Shroff, and E. S. Bentley, "Understanding the Impacts of Limited Channel State Information on Massive MIMO Cellular Network Optimization," IEEE Journal on Selected Areas in Communications (JSAC), accepted for publication.
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4. C. Joo, X. Lin, J. Ryu, and N. B. Shroff, "Distributed Greedy Approximation to Maximum Weighted Independent Set for Scheduling with Fading Channels," IEEE/ACM Trans. on Networking (ToN), vol. 24, no. 3, pp. 1476-1488, Jun. 2016.

Conferences:

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2. Z. Qian, F. Wu, Z. Zheng, K. Srinivasan, and N. B. Shroff, “Concurrent Channel Probing and Data Transmission in Full-duplex MIMO Systems,” ACM Mobihoc'17, accepted for publication.
3. A. M. Bedewy, Y. Sun, and N. B. Shroff, “Optimizing Data Freshness, Throughput, and Delay in Multi-Server Information-Update Systems,” IEEE ISIT'16, Barcelona, Spain, Jul., 2016.
4. J. Liu, A. Eryilmaz, N. B. Shroff, and E. Bentley, “Understanding the Impact of Limited Channel State Information on Massive MIMO Network Performances,” ACM Mobihoc'16, Paderborn, Germany, Jul., 2016.
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7. Y. Sun, E. Uysal-Biyikoglu, R. Yates, C. E. Koksal, and N. B. Shroff, “Update or Wait: How to Keep Your Data Fresh,” IEEE INFOCOM'16, San Francisco, CA, Apr. 2016. Technical report.
8. Z. Qian, B. Ji, K. Srinivasan, and N. B. Shroff, “Achieving Delay Rate-function Optimality in OFDM Downlink with Time-correlated Channels,” IEEE INFOCOM'16, San Francisco, CA, Apr. 2016.
9. S. Misra, X. Lin, N. Shroff, “Fast multi-channel Gibbs-sampling for clustering in cloud-based radio access networks,” 14th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Tempe, AZ, May 2016.