In this project, we carried significant amount of research innovation in wireless networking resource allocation, including the following: (1) the 3D tradeoff analysis provides a systematic and fair comparison of a variety of wireless scheduling algorithms in mobile ad hoc wireless networks, (2) the adaptive CSMA algorithm is the first utility optimal random access algorithm practically implemented on off the shelf commodity WiFi drivers, (3) new mathematical methods in stochastic approximation theory were developed in the process of proving utility optimal of the adaptive CSMA algorithm, (4) the first implementation and demonstration of optimal CSMA on wireless devices. It has lead to a large number of publications and the start of a tech transfer into DoD applications.
2.1 Summary

1. The 3D tradeoff analysis provides a systematic and fair comparison of a variety of wireless scheduling algorithms in mobile ad hoc wireless networks.

2. The adaptive CSMA algorithm is the first utility optimal random access algorithm practically implemented on off the shelf commodity WiFi drivers.

3. New mathematical methods in stochastic approximation theory were developed in the process of proving utility optimal of the adaptive CSMA algorithm.
4. The first implementation and demonstration of optimal CSMA on wireless devices.

2.2 Major Research Activities

The following results have been presented in multiple plenary and keynote speeches given by the PI, including those at IEEE INFOCOM, IEEE GLOBECOM, IEEE WiOpt, KU Leuven Simon Steven Lecture, and MIT LIDS Student Conference.

In an interference environment like wireless cellular or ad hoc networks, scheduling controls which link can transmit at each time slot and has been extensively studied since the 1960s. After the 1992 paper on maximum weight scheduling by Tassiulas and Ephremides, the research community has been developing simpler and more distributed scheduling algorithms that can still perform well in terms of throughput and delay.

In an ACM Mobihoc paper, we developed the first unifying framework of throughput-delay-complexity 3 dimensional tradeoff. Each scheduling algorithm is represented as a point in the 3D tradeoff space, and achievable tradeoff curves are extended through various parameterizations. This provides the first systematic way to compare a variety of scheduling algorithms in a fair way. Then in an ACM Mobihoc 2009 paper, we further developed the technique of heavy traffic approximation for wireless scheduling’s delay performance characterization. By proving the so called state space collapse property, we can reduce the dimensionality of the problem from $L$ links to 1 “representative” link. We showed that under heavy load and communication overhead in the scheduling algorithms, delay increases exponentially as the network grows.

Furthermore, in collaboration with Microsoft Research in UK, we were among the three teams that developed the first adaptive CSMA algorithm that can approach utility optimality arbitrarily tightly without using any explicit message passing. Each node can learn the interference environment purely based on the observed service rate in the past. Proving this result required substantial innovation in the mathematics of stochastic approximation theory and distributed optimization algorithm. This result also lead to new discoveries on transient behaviors of adaptive CSMA, such as the tradeoff between long-term efficiency and short-term fairness among the interfering links.

Then in a paper to appear in IEEE INFOCOM 2011, together with my former postdoc (now faculty at KAIST Korea) Yung Yi and collaborator Ed Knightly at Rice, we reported the first ever experimental implementation of optimal CSMA. We successfully implemented the theory inspired design onto conventional 802.11 drivers, offering a feasible path towards deployment. We also demonstrated the predictive power of theory, while discovering the gaps between theory and practice.

This further leads to a redesign by our team that bridged these gaps successfully. In 2012, we completed the first ever systems implementation of the redesigned optimal CSMA. This became the first demonstrated design that can provide near-optimal throughput in all key atomic topologies, including hidden nodes, information asymmetry, and flow in the middle. This success of bridging theory and practice has been documented in a submission to ACM CoNEXT conference recently. It has also started tech transfer path towards tactical military networks, as a defense contractor IAI has implemented it on their large scale wireless
emulation system and reproduced the results independently.

More generally, for high-dimensional, non-convex resource allocation problems in wireless networks, there is the practically important question of implementable and suboptimal algorithms. Protocol components in the current network architecture are often designed to attain certain optimality goals, with the hope that, when these optimal components work together, the overall network performance will also be optimized. However, for many network settings, due to either the scale of the network; the constraint on the response time of the algorithms; or the inherent non-convexity in the system, such optimal solutions can be difficult to attain. We have been exploring architectural choices that are robust to sub-optimality in each individual component. We argue that there is a need to shift our attention from optimal but complicated solutions, to easily implementable designs that are suboptimal but still possess good performance bounds. We studied the rate-allocation component of the network architecture, and investigated the following questions related to suboptimal components. (1) We investigated the robustness of the network architecture by studying how much sub-optimality the rate-allocation component can exhibit while the overall network architecture can still achieve satisfactory user-level performance. (2) We investigated how to tradeoff suboptimal rate-allocation with other performance measures, e.g., throughput and link utilization.

Our findings in a paper apppeared in IEEE/ACM Transactions on Networking demonstrate that it is possible to design an overall network architecture that is robust to suboptimal components. In particular, we show that even when the transport layer only computes suboptimal rate allocation, under suitable conditions the system can still achieve good user-level performance (in terms of achieving the largest connection-level stability region). Specifically, when the ratio of the utility gap (caused by a suboptimal rate allocation algorithm) to the maximum utility approaches zero as queue length tends to infinity, the maximum connection-level stability region can be retained. When the utility gap is in proportion to the maximum utility, only a reduced stability region can be achieved, in which case we provide a lower bound for the achievable stability regions. Not only that these results demonstrate how to characterize and design network architectures that are robust to suboptimal (but potentially simpler and easier-to-implement) rate-control, they also allow the network designer to intentionally under-optimize a given design objective, with the goal to improve other performance measures of the network.

2.3 Training and Development

Post-doc Hongseok Kim joined Bell Labs as a member of the technical staff. Graduate student Tian Lan graduated in 2010 and joined George Washington University as a tenure track Assistant Professor.

2.4 Outreach Activities

The subject of wireless scheduling was recently given as a keynote speech at IEEE WiOpt Conference in Seoul, Korea, by Chiang. Chiang has given numerous talks on architectures for wireless networks, especially on interference management and distributed scheduling,
to outline the intellectual challenges and engage the larger community in these promising research directions.

The first EDGE Lab Open House was held in April 2011 with a large number of participants from across the communities and networking industry, including a highlight on scheduling in MANET.

3 Publications

3.1 Journal Papers


3.2 Conference Papers


### 3.3 Invited Presentations


Telcordia Annual Strategic Research Review Keynote Speaker, Optimization in Networking, July 2010.


IPAM Optimization and Engineering Workshop, Optimizers on WiFi-Driver, December 2010.
