Editorial introduction

Queueing Syst (2012) 72:1–3
DOI 10.1007/s11134-012-9327-5

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Received: 18 August 2012 / Revised: 18 August 2012 / Published online: 7 September 2012

We are pleased to present this special issue "Recent Trends in the Mathematics of Wireless Communication Networks: Algorithms, Models, and Methods." Wireless communication systems have experienced a spectacular expansion over the last few decades, now providing the predominant means of Internet access. The capacity of these systems is constrained by a set of scarce resources such as radio frequencies, transmit power, and time slots. Information theory offers a powerful mathematical framework to understand how these transmission resources should be allocated so as to maximize the capacity at the physical layer, yielding valuable insights for the design of efficient schemes for, e.g., modulation, coding, and power control. Typically, however, information-theoretic models pertain to idealized scenarios: They do not account for random user behavior and dynamics at higher network layers; the practical application-specific performance requirements are largely ignored, and algorithmic implementation constraints are usually not considered. Designing systems while systematically addressing all of these aspects has posed major challenges in the last few decades. The vital need for wireless networks with significantly better performance has rejuvenated research activities toward tackling these challenges.

This special issue brings together a collection of twelve papers, divided in two volumes with six papers each, describing various recent advances in the mathematical treatment and stochastic analysis of wireless communication systems. A majority of these papers address the crucial issue of designing efficient schemes to share radio resources among various interfering links either in a centralized manner (cellular networks) or in a distributed fashion (wireless LANs or ad-hoc networks), accounting for user dynamics (packet or flow arrival processes) and fluctuating channel conditions. The typical objective is to devise resource sharing schemes providing stability (of the corresponding set of queues) whenever this is at all possible, and low packet or flow delays. This special issue also includes studies on the capacity and the design of multiple-access protocols for networks consisting of randomly located transmitters and receivers, relying on various advanced probabilistic methods, including stochastic geometry. Finally, this issue covers the analysis of wireless networks where information is disseminated using opportunistic contacts between nodes, and exploiting the mobility of these nodes.

The paper by Aalto, Lassila, Penttinen, and Osti considers the problem of scheduling elastic traffic flows in wireless systems. Assuming independent and identically distributed channel conditions, the paper shows how to optimally combine opportunistic and size-based scheduling in a transient setting. More specifically, using a time scale separation assumption, the authors develop a recursive algorithm that yields the optimal long-run service rate vectors. They also prove that the optimal scheduling policy applies the SRPT-FM principle, i.e., the shortest flow is served at the highest rate of the optimal rate vector, the second shortest flow at the second highest rate, etc. Moreover, it is explicitly described how to implement the optimal rate vectors in an actual time slot level opportunistic scheduler. In addition to the transient setting, the dynamic case with randomly arriving flows is explored via simulations. Interestingly, the scheduling policy that is optimal for the transient setting can be improved in the dynamic case by applying a rate-based priority scheduler that breaks the ties based on the SRPT principle.

The paper by Baccelli, Li, Richardson, Shakkottai, Subramanian, and Wu studies the performance of wide-area ad-hoc networks. The most popular medium access mechanism in such networks is CSMA/CA with RTS/CTS, where spatial reuse is implemented by energy-based guard zones. The paper specifically addresses the problem of simultaneously scheduling the maximum number of links that can achieve a given signal-to-interference ratio (SIR). Methods from stochastic geometry are used to evaluate and maximize the medium access probability of a typical link. The authors show that a simple modification to the RTS/CTS mechanism (replacing the energy level threshold by an SIR threshold) yields crucial performance gains. They also demonstrate that combined with an adaptation of the power level (setting it inversely proportional to the square root of the link gain), this significantly improves the throughput. Further, this power level selection is optimal in the absence of channel fading, and no worse than a factor of two away from optimal among the class of all local strategies in the presence of fading.

The paper by Frolkova, Foss, and Zwart considers ALOHA type random multiple-access protocols, which are commonly used to regulate networks with a star configuration where all client nodes talk to the hub node at the same frequency. Such protocols control who talks at what time, sharing the common idea "try to send your data and, if your message collides with another transmission, try resending later." The paper specifically deals with a time-slotted protocol where users are allowed to renege before transmission completion, and focuses on the scenario that leads to overload in the absence of impatience. Under mild assumptions, the authors show that the fluid (or law-of-large-numbers) limit of the system workload coincides almost surely with the unique solution to a certain integral equation. They also demonstrate that the fluid limits for distinct initial conditions converge to the same value as time tends to infinity.

The paper by Han and Makowski studies a spatial wireless network model consisting of a collection of n independent points which are distributed on the unit interval

[0, 1] according to some probability distribution function F. Two nodes communicate with each other if their distance is less than some given threshold value. When F admits a density f, which is strictly positive on [0, 1], the paper gives conditions on f under which the property of graph connectivity for the induced geometric random graph admits a very strong zero-one law when the transmission range is scaled appropriately with n large. The very strong critical threshold is identified by applying a version of the method of first and second moments.

The paper by Bonald and Feuillet considers the performance of CSMA in multichannel wireless networks, accounting for the random nature of traffic. The paper specifically assesses the ability of CSMA to fully utilize the radio resources and in turn stabilize the network in a dynamic setting with flow arrivals and departures. The authors show that CSMA is throughput-optimal in the ad-hoc mode, but not in the infrastructure mode, when all data flows originate from or are destined to some access points, due to the inherent bias of CSMA against downlink traffic. They then propose a slight modification of CSMA, referred to as flow-aware CSMA, which corrects this bias and makes the algorithm throughput-optimal in all cases. The analysis is based on a time scale separation assumption, which is proved to be valid in the limit of large flow sizes.

The paper by Jiang and Walrand addresses the design of distributed scheduling algorithms for networks of conflicting queues, where only specific subsets of queues can be served simultaneously. Such restrictions commonly arise in wireless networks due to spatial reuse constraints and interference among nodes. The challenge is to select the subsets in a distributed way to stabilize the queues whenever the arrival rates are within the capacity region. The paper gives an optimization formulation of the selection problem that involves the entropy of the distribution of the selected subsets. The dual algorithm for solving this optimization problem provides a distributed scheduling mechanism based on the CSMA protocol, which requires only local queue length information. The authors also examine the delay properties of these algorithms. In particular, they present a framework for queue stability under bounded CSMA parameters, and show how the expected queue lengths and delays depend on the throughput region to be supported. When the arrival rates are within a fraction of the capacity region, queue lengths that are polynomial (or even logarithmic) in the number of queues can be achieved.

The main credit for this special issue is due to the authors for their valuable contributions and the reviewers for their diligent efforts. We would also like to express our thanks to the editor-in-chief, Sergey Foss, for his constant encouragement and guidance as well as Aiza Policarpio and Sudha Subramanian in Springer's editorial office for their thoughtful support and dedication.

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