GAME THEORY IN WIRELESS NETWORKS

Luiz A. DaSilva *Hanna Bogucka* *Allen B. MacKenzie*

Game theory has been employed in the analysis of resource management in telecommunications networks for at least 20 years. As game theory has been traditionally applied to economic problems, it is not surprising that one of its first applications in telecommunications was in the study of pricing. In the early 1990s, researchers used game theory to propose new pricing strategies for Internet services. In the same decade, game theoretic models were developed for non-economic problems in networks, such as flow, admission, and congestion control. By the late 1990s and early 2000s, game theory was being applied to wireless networks.

As interest in decentralized wireless networks grew, so did the usefulness of game theoretic models to help us understand and predict the performance of complex wireless systems that cannot be completely modeled using traditional optimization tools. As radios become capable of more sophisticated adaptations, the assumptions of game theoretic models become a still better match for future wireless networks. Game theory is, after all, multi-agent decision theory, modeling rational, utility-maximizing agents whose actions affect one another's utilities.

Game theory has also captured popular imagination, with help from Sylvia Nasar's biography of John Nash, *A Beautiful Mind* (not to mention the Hollywood movie adaptation of the book). Nowadays, even researchers who are not directly involved with game theory are familiar with its basic concepts, such as the Nash equilibrium, and some toy examples, such as the prisoners' dilemma. But game theory extends much farther than these, with numerous refinements to the Nash equilibrium and different types of cooperative and non-cooperative games, each with its own set of assumptions and results on equilibrium existence and the convergence of distributed algorithms to such an equilibrium.

This issue features four articles that apply game theory to contemporary problems in wireless communications and networks. The application space represented is vast, as is the range of assumptions and types of games explored by the authors.

While the simplest game theoretic models assume that all players have complete information about each other's action spaces and objectives, it is possible to extend such models to consider how incomplete information affects the outcome. Sadguyu, Berry, and Ephremides apply Bayesian games to the problem of jamming in wireless networks. The incomplete information can be in terms of player type (e.g., a jammer that does not know whether there are radios in its vicinity that it would like to jam), utility function parameters (e.g., the energy costs of transmitting a packet and the energy costs of jamming), or the data traffic being supported by the network. By relaxing the assumptions on what a transmitter and a jammer know about each other, the authors are able to more realistically model denial of service attacks in wireless networks.

Uncertainty and Bayesian games are also the focus of the article by Akkarajitsakul, Hossain, and Niyato. However, instead of security issues, their application space is the problem of radio resource sharing in public wireless networks. Mobile users bid for bandwidth to support their applications, without complete knowledge of other users' mobility or demand. The system is modeled as a series of auctions, which take place in multiple rounds until all users' bandwidth requirements are met. The authors prove that a unique Bayesian Nash equilibrium exists for this problem and propose a distributed bidding algorithm to be followed by the mobile nodes.

Auction theory is more formally studied in the article by Iosifidis and Koutsopoulos. Dynamic spectrum access may create, as the name implies, a more dynamic market for spectrum. Auctions, which have long been studied using game theory, may prove to be lightweight and efficient methods for allocating spectrum to users and applications that can most benefit from it. Dynamic spectrum sharing imposes new requirements on auctions, due to the possibility of frequency reuse, the heterogeneous nature of the goods being auctioned off (different channels may experience different levels of interference, and their quality may vary with time), and the unpredictability of user demand and mobility. The authors discuss auction structures that account for these requirements, as well as the applicability of hierarchical auctions to dynamic leases on spectrum.

Also related to dynamic spectrum access, the concept of cognitive radio has sparked interest in the potential for radios to learn from the past to improve their performance and the performance of the network. Rose and his co-authors explore learning techniques such as best response, fictitious play, regret matching, and reinforcement learning applied to wireless communications. The authors compare these techniques in terms of how much knowledge of the overall environment each requires, and they present the convergence properties of each. The problem considered is that of multiple transceiver pairs competing for a set of frequency channels; each node applies learning mechanisms to decide on which channel to transmit to maximize its spectral efficiency.

While this is a small sample of current research at the intersection of game theory and wireless networks, we believe it illustrates the power of game theory to teach us about interactions in increasingly complex distributed wireless environments in which each node can make autonomous decisions that affect the entire network.

BIOGRAPHIES

LUIZ A. DASILVA [SM] (dasilval@tcd.ie) currently holds the Stokes Professorship in Telecommunications in the Department of Electronic and Electrical Engineering at Trinity College Dublin. He has also been a faculty member in the Bradley Department of Electrical and Computer Engineering at Virginia Tech since 1998. His research focuses on distributed and adaptive resource management in wireless networks, and in particular cognitive radio networks and the application of game theory to wireless networks. He is currently a principal investigator on research projects funded by the National Science Foundation in the United States, the Science Foundation Ireland, and the European Commission under Framework Programme 7. He is a co-principal investigator of CTVR, the Telecommunications Research Centre in Ireland. He has co-authored two books on wireless communications and over 90 peer-reviewed papers in leading journals and conferences on communications and networks. In 2006 he was named a College of Engineering Faculty Fellow at Virginia Tech.

HANNA BOGUCKA (hbogucka@et.put.poznan.pl) received her Ph.D. and Doctor Habilitus degrees in Telecommunications from Poznan University of Technology (PUT), Poland, in 1995 and 2006, respectively. Currently, she is a professor and deputy dean for research on the Faculty of Electronics and Telecommunications at PUT. She is involved in research activities in the area of wireless communications: radio resource management, opportunistic radio access, flexible, adaptive, and cognitive radio, and in particular the application of game theory toward the broadly understood efficiency of these systems. She has been involved in multiple European 5th–7th Framework Programme projects dealing with novel wireless flexible transmission techniques and cognitive radio technologies, as well as European COST actions. She is the author of book chapters and over 100 papers published in major IEEE journals and magazines, and in the proceedings of international conferences. She has also published three handbooks in the area of radio communications and digital signal processing (in Polish). She is a member of the Editorial Board of the journal *Advances in Electronics and Telecommunications*. She has been a technical program committee member of major IEEE ComSoc and VTS conferences (ICC, GLOBECOM, PIMRC, VTC), and she acts as a reviewer for *IEEE Transactions on Communications*, *IEEE Transactions on Information Theory*, IEEE Transactions on Vehicular Technology, and *IEEE Journal on Selected Areas in Communications*.

ALLEN B. MACKENZIE [SM] (mackenab@vt.edu) received his Bachelor's degree in electrical engineering and mathematics from Vanderbilt University in 1999. In 2003 he earned his Ph.D. in electrical engineering at Cornell University and joined the faculty of the Bradley Department of Electrical and Computer Engineering at Virginia Tech, where he is now an associate professor. His research focuses on wireless communications systems and networks. His current research interests include cognitive radio and cognitive network algorithms, architectures, and protocols, and the analysis of such systems and networks using game theory. His past and current research sponsors include the National Science Foundation, the Defense Advanced Research Projects Agency, and the National Institute of Justice. He is a member of the ASEE and ACM. In 2006 he received the Dean's Award for Outstanding New Assistant Professor in the College of Engineering at Virginia Tech. He is the author of more than 45 refereed conference and journal papers, and a co-author of the book *Game Theory for Wireless Engineers*.