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Fundamental Performance Limits in Cross-layer Wireless Optimization: Throughput, Delay, and Energy

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Fundamental Performance Limits in Cross-layer Wireless Optimization: Throughput, Delay, and Energy

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Abstract

In recent years, one of the most significant developments in both the theory and practice of communication and networking has been the closer coupling between the design of physical-layer functionalities such as coding and modulation, and the design of higher-layer functionalities such as contention resolution and scheduling. This closer coupling is characteristic of the *cross-layer* paradigm. It is the objective of the present survey to spell out some of the basic challenges, key communication settings, and crucial results, relevant to cross-layer analysis and design for wireless systems. This work focuses primarily on communication settings relevant to wireless cellular communications, where cross-layer design principles have arguably had the greatest impact on practical systems. In order to explore the fundamental performance limits of wireless systems operating under the cross-layer paradigm, the survey shows how information theory and network theory can be leveraged to study issues such as channel modeling, coding, source burstiness, throughput, delay, multi-user

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interference, multi-path fading, and energy constraints in a more coherent overall analytical and design framework.

The survey first examines multiaccess communication channels, the simplest example of a network setting where multiple users share a communication medium. It reviews some of the pioneering work in extending information theory to incorporate source burstiness and queueing. It then examines cross-layer design approaches for multiaccess (uplink) fading channels in wireless communications. The key concepts of stability region, throughput optimality, and delay optimality are introduced. Optimal algorithms which maximize throughput and minimize delay for multiaccess fading channels with random arrivals and queueing are characterized. Next, the survey focuses on a similar setting for communication over broadcast (downlink) fading channels, and introduce relevant results. Finally, it examines the fundamental performance tradeoffs between power and delay in single-user and multi-user communication over wireless channels with energy constraints.

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1

Introduction

Over the last twenty years, dramatic advances in wireless technology have redefined the basic terms of modern living. In bringing about the wireless revolution, both the theory and practice of communication and networking have had to adapt and evolve in fundamental ways. Perhaps one of the most significant changes is the much closer coupling between the design of physical-layer functionalities such as coding and modulation, and the design of higher-layer functionalities such as contention resolution, scheduling, routing, and congestion control. This closer coupling is characteristic of the *cross-layer* paradigm, which has strongly influenced the design and implementation of wireless systems since the beginning of the century [8, 31, 56]. It is the objective of the present survey to spell out some of the basic challenges, key communication settings, and crucial results, relevant to cross-layer analysis and design for wireless systems. Given the wide impact of the cross-layer paradigm over the last decade, we do not attempt a comprehensive survey. Rather, we shall focus primarily on communication settings relevant to wireless cellular communications, where cross-layer design principles have arguably had the greatest impact on practical systems. In these settings, the complex interactions among the physical, data

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link control, and medium access control layers of the network stack present both challenges and opportunities for enhancing network performance. In order to explore the fundamental performance limits of wireless systems operating under the cross-layer paradigm, we examine how information theory and network theory can be leveraged to study issues such as channel modeling, coding, source burstiness, throughput, delay, multi-user interference, multi-path fading, and energy constraints, in a more coherent overall analytical and design framework.

1.1 Layering

The original seven-layer Open System Interconnection (OSI) framework was developed primarily for wireline networks. While the OSI layering hierarchy introduced much needed modularity and standard interfaces into the network architecture, it also suffered from problems which were apparent from the beginning. For example, it has been pointed out [21] that multiaccess mechanisms (which contain elements of physical, data link, and network layer mechanisms) do not fit naturally into the OSI layering scheme. Nevertheless, the layering concept became dominant over the years in the field of networking, and in some ways led to a separation of research communities which were focused on attacking problems relevant to specific network layers.

In a sense, however, the emergence of the OSI layered architecture as a practical design paradigm was very natural. For networking lacked (and still lacks) a fundamental theory which could explain and exploit all the intricate coupling between various network functionalities. For a long time, information theory, the foundational theory for communication, influenced networking mostly through the physical layer, where coding, modulation, and detection were the main focus. Information theory's potential impact on the other network layers has been limited in part by its inability to adequately account for *source burstiness* and the role of *delay* as a key network parameter [27].

1.2 Information Theory and Network Theory

In networks, messages typically arrive at random instants, or in a bursty manner, to transmitters. In information theory, however, it is typically

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assumed that there are infinite reservoirs of information bits arriving at all transmitters, so that all users of the channel always have bits to send. While this modelling assumption may be reasonable for the point-to-point wireline link (for which information theory was originally designed) [27], it is far from appropriate for network communication situations, where source burstiness is central to the problem of resource sharing among different users [21, 27]. Furthermore, source coding or source ergodicity cannot be relied upon for smoothing over the source burstiness, since the time scale required would be much larger than the acceptable network delay. This implies that it is very difficult to perform any meaningful analysis of network delay within the traditional information theory setting. Thus, while the information theory framework does a fine job in statistically modelling the communication channel, and in capturing the performance tradeoffs among quantities such as communication rate and error probability, it cannot easily characterize tradeoffs involving higher-layer quality of service (QOS) quantities such as delay [8].

While the information theory approach focuses on physical-layer issues, somewhat at the expense of higher-layer QOS issues, traditional network theory does almost the opposite. Network theory gives sophisticated analysis of issues such as source burstiness, network delay, and buffer overflow, but often make simplistic assumptions concerning channel modeling, coding, and detection. For instance, the characterization of the multiaccess channel as a collision channel is too simplified and pessimistic from a physical layer viewpoint. Thus, while the information theory and network theory approaches offer different perspectives, each addresses only a part of the overall problem. In practice, there exists a "bit pipe" abstraction in traditional networking, where as far as the layers above the physical and data link layers are concerned, the communication link is a bit pipe with a given rate suffering occasional random errors. Research in the networking community tends to focus on optimally allocating these bit pipes to randomly arriving traffic, using techniques such as scheduling and contention resolution, in order to optimize QOS metrics such as throughput and delay. Research in the information theory and communication communities tends to focus on building better bit pipes, using various coding, modulation,

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and detection techniques, in order to optimize physical-layer metrics such as energy per bit and spectral efficiency [8]. This effective division has been caused partly by the lack of a coherent overall theory, and partly by the OSI layering structure itself. With some notable exceptions (some of which will be explored in detail later in the survey), the division continued until the end of the twentieth century. It was then that Ephremides and Hajek, in a well-known survey paper [21], outlined the challenges for the information theory and networking communities in addressing this division. Fortunately, the tide began to turn shortly after the appearance of the survey paper. The major impetus for the turn was the increasing importance of *wireless* communication and networking.

1.3 Wireless Communication

Three prominent issues in wireless communication are: interference among multiple users, the time-varying nature of the wireless channel, and the limited energy resources of mobile devices. All three issues accentuate the need for cross-layer design. Since multiple users interfere within the inherently shared wireless medium, it is clear that the stochastic nature of user activity is a key consideration. Furthermore, the choice of the physical layer coding and modulation scheme has important implications for how the multi-user interference is resolved. For instance, whether the system uses a collision model (i.e., only one user can successfully transmit at one time), CDMA (where multiple users can send and be decoded simultaneously), or more advanced multi-user coding techniques based on information theory, has a direct impact on the performance of the wireless network.

Due to shadowing and multipath fading, the quality of wireless channels can vary dramatically in both time and frequency. In stark contrast to communication over point to point wireline channels, where there is little need to consider variable transmission power and rate, wireless communication can gain substantially from channel measurement feedback, adaptive transmission power and rate allocation. For instance, the optimal strategy for maximizing long-term throughput over a single-user fading wireless channel (with channel side information

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at both the transmitter and receiver) involves a "waterfilling" strategy where the transmitter sends more information in good channel states and less or no information in poor channel states [30]. Within a multi-user communication setting, a still more striking phenomenon called *multi-user diversity* emerges. This is the observation that as the number of users (with independent and identically distributed channel fading processes) in a system increases, the probability that some user has a very good channel state also increases. Properly exploiting the diversity allows one to obtain a system capacity which is increasing with the number of users [40]. Finally, channel fading introduces a new source of randomness (in addition to background noise) to the coding problem. Any sensible coding scheme must somehow average over both sources of randomness. This raises the important question of how large the decoding delay requirement is relative to the time scale of the fading process. When the encoder/decoder pair has enough time to average over the fading process, traditional information-theoretic notions of ergodic capacity are relevant (in the sense that they provide meaningful benchmarks for performance analysis). If not, alternative measures of performance such as capacity versus outage [51] and delay-limited capacity [37] are more appropriate.

Yet another fundamental difference between wireline and wireless sytems is the limited energy sources available for mobile devices. Whereas wireline devices can typically operate at peak power and rate, mobile wireless devices must optimize their transmission strategy over fading channels to conserve battery power, maximize device lifetime, while still meeting requirements on data rate, error probability, as well as higher layer QOS metrics such as delay. This is a task which clearly requires coordination across a number of different network layers. What is clear from this discussion is that the "bit pipe" abstraction of the physical layer discussed earlier simply does not suffice for the wireless context. A much richer abstraction is needed [8].

1.4 Outline

This survey will review some key problem settings and results where the cross-layer design paradigm has significantly influenced our

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understanding of communication systems in recent years. We will primarily focus on communication scenarios which are most important for wireless cellular communications: single-user, multiaccess (many transmitters and one receiver), and broadcast (one transmitter and many receivers). In all these problem settings, it will become apparent that many of the key physical-layer results in wireless communication developed during the 1990s need to be adapted and amended when higher level QOS metrics are taken into account in the process of system design. For a good survey of cross-layer control and resource allocation techniques for multi-hop wireless networks, we refer the reader to [29].

The rest of the survey proceeds as follows. In Section 2, we examine multiaccess communication channels, the simplest example of a network setting where multiple users share a communication medium. We will review some of the pioneering work in extending information theory to incorporate source burstiness and queueing. We then examine cross-layer design approaches for multiaccess (uplink) fading channels in wireless communications. The key concepts of stability region, throughput optimality and delay optimality are introduced. Optimal algorithms which maximize throughput and minimize delay for multiaccess fading channels with random arrivals and queueing are characterized. In Section 3, we examine a similar setting for communication over broadcast (downlink) fading channels, and introduce relevant results. Finally, in Section 4, we examine the fundamental performance tradeoffs between power and delay in single-user and multi-user communication over wireless channels with energy constraints. In our exposition, we focus primarily on information-theoretic settings, since we are interested in fundamental performance limits. Nevertheless, the cross-layer framework we examine here applies equally well to communication systems with other coding and modulation schemes.

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References

[1] R. Ahlswede, "Multi-way communication channels," in *Proceedings of International Symposium on Information Theory*, pp. 23–52, 1971.

[2] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, and P. Whiting, "Providing quality of service over a shared wireless link," *IEEE Communications Magazine*, vol. 39, no. 2, pp. 150–154, 2001.

[3] P. Bergmans, "Random coding theorem for broadcast channels with degraded components," *IEEE Transactions on Information Theory*, vol. 19, no. 2, pp. 197–207, 1973.

[4] P. Bergmans, "A simple converse for broadcast channels with additive white gaussian noise," *IEEE Transactions on Information Theory*, vol. 20, no. 2, pp. 279–280, 1974.

[5] R. Berry, "Power and delay trade-offs in fading channels," PhD thesis, Massachusetts Institute of Technology, Cambridge, MA, June, 2000.

[6] R. Berry, "Power and delay optimal scheduling: Small delay asymptotics," in *Proceedings of 2003 IEEE International Symposium on Information Theory*, Yokohama, Japan, June 29–July 4 2003.

[7] R. Berry and R. Gallager, "Communication over fading channels with delay constraints," *IEEE Transactions on Information Theory*, vol. 48, pp. 1135–1149, May 2002.

[8] R. Berry and E. Yeh, "Cross-layer wireless resource allocation," *IEEE Signal Processing Magazine*, vol. 21, no. 5, pp. 59–68, 2004.

[9] D. Bertsekas, *Dynamic Programming and Optimal Control.* Belmont, MA: Athena Scientific, 1995.

[10] D. Bertsekas and R. Gallager, *Data Networks.* NJ: Prentice Hall, 1992.

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- [11] I. Bettesh and S. Shamai, "Optimal power and rate control for minimal average delay: The single-user case," *IEEE Transactions on Information Theory*, vol. 52, pp. 4115–4141, September 2006.
- [12] J. Blazewicz, K. Ecker, E. Pesch, G. Schmidt, and J. Weglarz, *Scheduling Computer and Manufacturing Processes*. Berlin: Springer, 1996.
- [13] H. Boche, E. Jorswieck, and T. Haustein, "Channel aware scheduling for multiple antenna multiple access channels," in *Conference Record of the Asilomar Conference on Signals, Systems and Computers, 2003*, vol. 1, pp. 992–996, November 2003.
- [14] H. Boche and M. Wiczanowski, "Queueing theoretic optimal scheduling for multiple input multiple output multiple access channel," in *Proceedings of the IEEE International Symposium on Signal Processing and Information Technology 2003*, pp. 576–579, December 2003.
- [15] H. Boche and M. Wiczanowski, "Stability region of arrival rates and optimal scheduling for mimo-mac-a cross-layer approach," in *2004 International Zurich Seminar on Communications*, pp. 18–21, 2004.
- [16] B. Collins and R. Cruz, "Transmission policies for time varying channels with average delay constraints," in *Proceedings of 2001 Allerton Conference on Communication, Control, and Computing*, 1999.
- [17] T. Cover, "Broadcast channels," *IEEE Transactions on Information Theory*, vol. 18, no. 1, pp. 1–14, 1972.
- [18] T. Cover and J. Thomas, *Elements of Information Theory*. New York: Wiley, 1991.
- [19] E. Ehsan and T. Javidi, "Delay optimal transmission policy in a wireless multiaccess channel," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3745–3751, 2008.
- [20] A. El Gamal, C. Nair, B. Prabhakar, E. Uysal-Biyikoglu, and S. Zahedi, "Energy-efficient scheduling of packet transmissions over wireless networks," in *INFOCOM 2002. Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 3, pp. 1773–1782, 2002.
- [21] A. Ephremides and B. Hajek, "Information theory and communication networks: An unconsummated union," *IEEE Transactions on Information Theory*, vol. 44, no. 6, pp. 2416–2434, 1998.
- [22] A. Eryilmaz, R. Srikant, and J. Perkins, "Stable scheduling policies for broadcast channels," in *Proceedings of International Symposium on Information Technology*, p. 382, 2002.
- [23] A. Fu, E. Modiano, and J. Tsitsiklis, "Optimal energy allocation for delay-constrained data transmission over a time-varying channel," in *Proceedings of IEEE INFOCOM 2003*, San Francisco, CA, April 2003.
- [24] A. Fu, E. Modiano, and J. Tsitsiklis, "Optimal transmission scheduling over a fading channel with energy and deadline constraints," *IEEE Transactions on Wireless Communications*, vol. 5, pp. 630–641, March 2006.
- [25] R. Gallager, *Information Theory and Reliable Communication*. New York: Wiley, 1968.
- [26] R. Gallager, "Coding and capacity for degraded broadcast channels," *Problemy Peridachi Informatsii*, 1974.

Full text available at: http://dx.doi.org/10.1561/0100000014

[27] R. Gallager, "A perspective on multiaccess channels," *IEEE Transactions on Information Theory*, vol. 31, no. 2, pp. 124–142, 1985.

[28] E. Gelenbe and I. Mitrani, *Analysis and Synthesis of Computer Systems.* New York: Academic Press, 1980.

[29] L. Georgiadis, M. J. Neely, and L. Tassiulas, "Resource allocation and cross-layer control in wireless networks," *Foundations and Trends in Networking*, vol. 1, pp. 1–144, April 2006.

[30] A. Goldsmith and P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Transactions on Information Theory*, vol. 43, pp. 1986–1992, 1997.

[31] A. Goldsmith and S. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Communications*, vol. 9, pp. 8–27, 2002.

[32] T. Gonzalez, "Optimal mean finish time preemptive schedules," Technical Report, Pennsylvania State University, Computer Science Department, 1977.

[33] V. Goyal, A. Kumar, and V. Sharma, "Power constrained and delay optimal policies for scheduling transmission over a fading channel," in *Proceedings of IEEE INFOCOM 2003*, San Francisco, March 30–April 3 2003.

[34] V. Goyal, A. Kumar, and V. Sharma, "Optimal cross-layer scheduling of transmissions over a fading multiaccess channel," *IEEE Transactions on Information Theory*, vol. 54, pp. 3518–3537, August 2008.

[35] A. Grant and L. Rasmussen, "A new coding method for the asynchronous multiple access channel," in *Proceedings of the Allerton Conference on Communication, Control, and Computing*, Monticello, IL, 1995.

[36] A. Grant, B. Rimoldi, R. Urbanke, and P. Whiting, "Rate-splitting multiple access for discrete memoryless channels," *IEEE Transactions on Information Theory*, vol. 47, no. 3, pp. 873–890, 2001.

[37] S. Hanly and D. Tse, "Multi-access fading channels: Part II: Delay-limited capacities," *IEEE Transactions on Information Theory*, vol. 44, pp. 2816–2831, November 1998.

[38] F. Kelly, *Reversibility and Stochastic Networks.* New York: Wiley, 1979.

[39] I. Keslassy, M. Kodialam, and T. Lakshman, "Faster algorithms for minimum-energy scheduling of wireless data transmissions," in *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt '03)*, France, March 2003.

[40] R. Knopp and P. Humblet, "Information capacity and power control in single-cell multiuser communications," in *Proceedings of International Conference on Communications*, Seattle, WA, 1995.

[41] R. Laroia, S. Uppala, and J. Li, "Designing a broadband mobile wireless network: An integrated approach," *IEEE Signal Processing Magazine*, vol. 21, pp. 20–28, 2004.

[42] R. Leelahakriengkrai and R. Agrawal, "Scheduling in multimedia wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 52, pp. 226–239, 2003.

[43] E. Leonardi, M. Mellia, F. Neri, and M. Marson, "Bounds on average delays and queue size averages and variances in input-queued cell-based switches," in *Proceedings of Infocom 2001*, pp. 1095–1103, 2001.

Full text available at: http://dx.doi.org/10.1561/0100000014

[44] L. Li and A. Goldsmith, "Capacity and optimal resource allocation for fading broadcast channels: Part I: Ergodic capacity," *IEEE Transactions on Information Theory*, vol. 47, no. 3, pp. 1083–1102, 2001.

[45] H. Liao, "Multiple access channels," PhD thesis, University of Hawaii, Department of Electrical Engineering, 1972.

[46] A. Marshall and I. Olkin, *Inequalities: Theory of Majorization and Its Applications*. New York: Academic Press, 1979.

[47] S. Musy, "Delay and coding in multiple-user communications," PhD thesis, EPFL, Lausanne, Switzerland, 2007.

[48] M. J. Neely, "Energy optimal control for time varying wireless networks," in *Proceedings of Infocom*, Miami, 2005.

[49] M. J. Neely, E. Modiano, and C. E. Rohrs, "Power and server allocation in a multi-beam satellite with time varying channels," in *Proceedings of Infocom 2002*, New York City, 2002.

[50] M. J. Neely, E. Modiano, and C. E. Rohrs, "Dynamic power allocation and routing for time varying wireless networks," in *Proceedings of Infocom*, San Francisco, 2003.

[51] L. Ozarow, S. Shamai, and A. Wyner, "Information theoretic considerations for mobile radio," *IEEE Transactions on Vehicular Technology*, vol. 43, pp. 359–378, May 1994.

[52] B. Prabhakar, E. Uysal-Biyikoglu, and A. E. Gamal, "Energy-efficient transmission over a wireless link via lazy packet scheduling," in *Procedings of IEEE Infocom 2001*, 2001.

[53] S. Raj, E. Telatar, and D. Tse, "Job scheduling and multiple access," in *DIMACS Series in Discrete Mathematics and Theoretical Computer Science: Advances in Network Information Theory*, vol. 66, (P. Gupta, G. Kramer, and A. van Wijnggaarden, eds.), pp. 127–137, American Mathematical Society, 2004.

[54] B. Rimoldi, "Generalized time sharing: A low-complexity capacity-achieving multiple-access technique," *IEEE Transactions on Information Theory*, vol. 47, pp. 2432–2442, 2001.

[55] B. Rimoldi and R. Urbanke, "A rate-splitting approach to the gaussian multiple-access channel," *IEEE Transactions on Information Theory*, vol. 42, pp. 364–375, 1996.

[56] S. Shakkottai and P. C. Karlsson, "Cross-layer design for wireless networks," *IEEE Communications Magazine*, vol. 41, pp. 74–80, 2003.

[57] S. Shakkottai and A. L. Stolyar, "Scheduling for multiple flows sharing a time-varying channel: The exponential rule," in *Analytic Methods in Applied Probability. In Memory of Fridrih Karpelevich*, (Y. Suhov, ed.), Providence, R.I: American Mathematical Society, 2002.

[58] L. Tassiulas and A. Ephremides, "Dynamic server allocation to parallel queues with randomly varying connectivity," *IEEE Transactions on Information Theory*, vol. 39, no. 2, pp. 466–478, 1993.

[59] I. E. Telatar and R. Gallager, "Combining queueing theory with information theory for multiaccess," *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 6, pp. 963–969, 1995.

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[60] D. Tse, “Optimal power control over parallel Gaussian broadcast channels,” *Manuscript*, 1998.

[61] D. Tse and S. Hanly, “Multi-access fading channels: Part I: Polymatroid structure, optimal resource allocation and throughput capacities,” *IEEE Transactions on Information Theory*, vol. 44, no. 7, pp. 2796–2815, 1998.

[62] E. Uysal-Biyikoglu and A. E. Gamal, “On adaptive transmission for energy efficiency in wireless data networks,” *IEEE Transactions on Information Theory*, vol. 50, pp. 3081–3094, December 2004.

[63] E. Uysal-Biyikoglu, B. Prabhakar, and A. E. Gamal, “Energy-efficient packet transmission over a wireless link,” *IEEE Transactions on Networking*, vol. 10, pp. 487–499, August 2002.

[64] S. Verdu, “Wireless bandwidth in the making,” *IEEE Communications Magazine*, vol. 38, pp. 53–58, 2002.

[65] D. Welsh, *Matroid Theory*. London: Academic Press, 1976.

[66] J. Yang and S. Ulukus, “Delay minimization in multiple access channels,” in *Proceedings of the International Symposium on Information Theory*, 2009.

[67] E. Yeh, “Multiaccess and fading in communication networks,” PhD thesis, Massachusetts Institute of Technology, 2001.

[68] E. Yeh, “An inter-layer view of multiaccess communications,” in *Proceedings of the 2002 International Symposium on Information Theory*, p. 112, Lausanne, Switzerland, 2002.

[69] E. Yeh, “Delay optimal multiaccess communication for general packet length distributions,” in *Proceedings of the International Symposium on Information Theory*, Chicago, IL, 2004.

[70] E. Yeh, “Minimum delay multiaccess communication for general packet length distributions,” in *Proceedings of Allerton Conference on Communication, Control, and Computing*, 2004.

[71] E. Yeh and A. Cohen, “Throughput and delay optimal resource allocation in multiaccess fading channels,” in *Proceedings of the International Symposium on Information Theory*, p. 245, Yokohama, Japan, 2003.

[72] E. Yeh and A. Cohen, “Delay optimal rate allocation in multiaccess fading communications,” in *Proceedings of Allerton Conference on Communication, Control, and Computing*, 2004.

[73] E. Yeh and A. Cohen, “Information theory, queueing, and resource allocation in multi-user fading communications,” in *Proceedings of the Conference on Information Sciences and Systems*, Princeton, NJ, 2004.

[74] E. Yeh and A. Cohen, “Throughput optimal power and rate control for queued multiaccess and broadcast communications,” in *Proceedings of the International Symposium on Information Theory*, Chicago, IL, 2004.

[75] E. Yeh and R. Gallager, “Achieving the multiple access capacity region via projective time sharing,” in *Proceedings of the 1998 International Symposium on Information Theory*, p. 213, Cambridge, Massachusetts, 1998.

[76] M. Zafer and E. Modiano, “A calculus approach to minimum energy transmission policies with quality of service guarantees,” in *Proceedings of IEEE Infocom 2005*, Miami, FL, 2005.

[77] M. Zafer and E. Modiano, “A calculus approach to energy-efficient data transmission with quality-of-service constraints,” *IEEE/ACM Transactions on Networking*, vol. 17, pp. 898–911, June 2009.