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Foundations and Trends® in Networking

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PO Box 1024
Hanover, MA 02339
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Tel. +1-781-985-4510
www.nowpublishers.com
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Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is P. C. Weeraddana, M. Codreanu, M. Latva-aho, A. Ephremides and C. Fischione, Weighted Sum-Rate Maximization in Wireless Networks: A Review, Foundation and Trends® in Networking, vol 6, nos 1-2, pp 1–163, 2011

ISBN: 978-1-60198-582-8

Foundations and Trends® in Networking

Volume 6 Issues 1-2, 2011

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Foundations and Trends® in Networking, 2011, Volume 6, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in
Networking
Vol. 6, Nos. 1-2 (2011) 1–163

DOI: 10.1561/1300000036

Weighted Sum-Rate Maximization in Wireless Networks: A Review

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Abstract

A wide variety of resource management problems of recent interest, including power/rate control, link scheduling, cross-layer control, network utility maximization, beamformer design of multiple-input multiple-output networks, and many others are directly or indirectly reliant on the weighted sum-rate maximization (WSRMax) problem. In general, this problem is very difficult to solve and is NP-hard. In this review, we provide a cohesive discussion of the existing solution methods associated with the WSRMax problem, including global, fast local, as well as decentralized methods. We also discuss in depth the applications of general optimization techniques, such as branch and bound methods, homotopy methods, complementary geometric programming, primal decomposition methods, subgradient methods, and sequential approximation strategies, in order to develop algorithms for the WSRMax problem. We show, through a number of numerical examples, the applicability of these algorithms in various application domains.

Contents

1

Introduction

Consider a general wireless network with L interfering links. The achievable rate of each link is a scalar function and is denoted by r_l. Then the general weighted sum-rate maximization (WSRMax) problem has the form:

$$\begin{array}{ll} \text{maximize} & \sum_{l=1}^{L} \beta_l r_l(\mathbf{y}) \\ \text{subject to} & \mathbf{y} \in \mathcal{Y}. \end{array} \tag{1.1}$$

Here $\mathbf{y} = (y_1, \ldots, y_n)$ is the optimization variable of the problem, positive scalar β_l is the weight associated with link l, and the (possibly nonconvex) set $\mathcal{Y}$ is the feasible set of the problem. In general, r_l is not convex in $\mathbf{y}$. Therefore, problem (1.1) is surprisingly *difficult* to solve, though it appears to be very simple.

In this section, we first provide a discussion that emphasizes the importance of WSRMax problem (1.1) in wireless networks. Next we discuss the importance of global, fast local, as well as distributed solution methods for WSRMax problem. Finally, the existing key literature that address the problem is presented. Applications of optimization techniques for developing algorithms for the problem will be covered in later sections, with more technical detail.

1.1 Motivation

Among various resource management policies, the WSRMax for an arbitrary set of interfering links plays a central role in many network control and optimization methods. For example, the problem is encountered in network utility maximization (NUM) [88], the resource allocation (RA) subproblem in various cross-layer control policies [43, 81], MaxWeight link scheduling in multihop wireless networks [120], power/rate allocation in wireless networks, as well as in wireline networks [115, 124], joint optimization of transmit beamforming patterns, transmit powers, and link activations in multiple-input multiple-output (MIMO) networks [34], and finding achievable rate regions of singlecast/multicast wireless networks [87], among others.

1.1.1 Network Utility Maximization (NUM)

In the late nineties, Kelly et al. [59, 60] introduced the concept of NUM for fairness control in wireline networks. It was shown therein that maximizing the sum-rate under the fairness constraint is equivalent to maximizing certain network utility functions and different network utility functions can be mapped to different fairness criteria. For a useful discussion of many aspects of the NUM concept in the case of wireless network, see [88] and the references therein. In this context, the WSRMax problem appears as a part of the Lagrange dual problem of the overall NUM problem; see [89] and the references therein.

1.1.2 Cross-layer Control Policies for Wireless Networks

For useful discussions of cross-layer control policies, see [40, 43, 68, 71, 81, 90, 142] and the references therein. Many of these policies are essentially identical. It has been shown that an optimal cross-layer control policy, which achieves data rates arbitrarily close to the optimal operating point, can be decomposed into three subproblems that are normally associated with different network layers. Specifically, *flow control* resides at the transport layer, *routing and in-node scheduling*[1] resides

[1] *in-node scheduling* refers to selecting the appropriate commodity and it is not to be confused with the links scheduling mechanism which is handled by the resource allocation subproblem [43].

at the network layer, and *resource allocation* (or RA) is usually associated with the medium access control and physical layers [43]. The first two subproblems are convex optimization problems and can be solved relatively easily. It turns out that under reasonably mild assumptions, the RA subproblem can be cast as a general WSRMax problem over the instantaneous achievable rate region [43]. The weights of the links are given by the differential backlogs and the policy resembles the well-known *backpressure algorithm* introduced by Tassiulas and Ephremides in [120, 121] and further extended by Neely to dynamic networks with power control; see [81] and the references therein.

1.1.3 MaxWeight Link Scheduling for Wireless Networks

Maximum weighted link scheduling for wireless networks [41, 68, 105, 120, 121, 138] is a place, in which the problem of WSRMax is directly used. Note that, for networks with fixed link capacities, the maximum weighted link scheduling problem reduces to the classical maximum weighted matching problem and can be solved in polynomial time [68]. However, no solution is known for the general case when the link rates depend on the power allocation of all other links.

1.1.4 Power/rate Control Policies

We see sometimes that the WSRMax problem is directly used as the basis for the power/rate control policy in wireless, as well as in wireline networks [115, 124]. For example, in DSL networks, there is considerable research on resource management policies, which rely directly on the WSRMax problem for multiuser spectrum balancing [3, 27, 28, 39, 74, 94, 97, 127, 128, 129, 139, 140]. Direct application of WSRMax as an optimization criterion can also been seen extensively in joint power control and subcarrier assignment algorithms for OFDMA networks [7, 50, 54, 67, 104, 106, 145].

1.1.5 Resource Management in MIMO Networks

There are also a number of resource management algorithms in multiuser MIMO networks, which rely on the problem of WSRMax. For example, the methods proposed in [34, 35, 111, 122] rely on WSRMax for joint design of linear transmit and receive beamformers. In addition, many references have applied WSRMax directly as an optimization criterion for beamformer design in MIMO networks, e.g., [45, 151].

1.1.6 Finding Achievable Rate Regions in Wireless Networks

In multiuser systems many users share the same network resources, for example, time, frequency, codes, space, etc. Thus, there is naturally a tradeoff between the achievable rates of the users. In other words, one may require to reduce its rate if another user wants a higher rate. In such multiuser systems, the achievable rate regions are important since they characterize the tradeoff achievable by any resource management policy [124]. By invoking a time sharing argument, one can always assume that the rate region is convex [124]. Therefore, any boundary point of the rate region can be obtained by using the solution of a WSRMax problem for some weights.

Thus, WSRMax is a central component in many network design problems as we discussed above. Unfortunately, the general WSRMax problem is not yet amendable to a convex formulation [76]. In fact, it is NP-hard [75]. Therefore, we must rely on global optimization approaches [5, 52] for computing an exact solution of the WSRMax problem. Such global solution methods are increasingly important because they can be used to provide performance benchmarks by back-substituting them into any network design method, which relies on WSRMax. They are also very useful for evaluating the performance loss encountered by any heuristic algorithm for the WSRMax problem.

Although global methods find the solution of the WSRMax problem, they are typically slow. Even small problems, with a few tens of variables, can take a very long time to solve WSRMax. Therefore, it is natural to seek suboptimal algorithms for WSRMax that are efficient enough, and still close to optimal; the compromise is optimality [22]. Such algorithms are of central importance since they can be fast and widely applicable in large-scale network control and optimization methods.

Due to the explosion of problem size and the signal overhead required in centralized network control and optimization methods, it is highly desirable to develop decentralized variants of those algorithms. Therefore, finding distributed methods for the WSRMax problem is of crucial importance from a theoretical, as well as from a practical perspective for decentralized implementation of many network control and optimization methods, such as those investigated in [81, 120].

1.2 Global Methods for WSRMax in Wireless Networks

The general WSRMax problem is NP-hard [75]. It is therefore natural to rely on global optimization approaches [5, 52] for computing an exact solution. One straightforward approach is based on exhaustive search in the variable space [28]. The main disadvantage of this approach is the prohibitively expensive computational complexity, even in the case of very small problems. A better approach is to apply branch and bound techniques [52], which essentially implement the exhaustive search in an intelligent manner; see [3, 39, 57, 97, 129, 135, 139]. Branch and bound methods based on difference of convex functions (DC) programming [52] have been proposed in [3, 39, 139] to solve (a subclass of) WSRMax. Although DC programming is the core of their algorithms, it also limits the generality of their method to the problems in which the objective function cannot easily be expressed as a DC [52]. For example, in the case of multicast wireless networks, expressing the objective function as a DC cannot be easily accomplished, even when Shannon's formula is used to express the achievable link rates. Another branch and bound method has been used in [129] in the context of DSL bit loading, where the search space is discretized in advance. As a result of discretization, this method does not allow a complete control of the accuracy of the solution. An alternative optimal method was proposed in [97], where the WSRMax problem is cast as a generalized linear fractional program [96] and solved via a polyblock algorithm [48]. The method works well for small scale problems, but as pointed out in [5, chap. 2, pp. 40–41] and [96, sec. 6.3], it may show much slower convergence than branch and bound methods as the problem size increases. A special form of the WSRMax problem is presented in [23, p. 78] [128], where the problem data and the constraints must obey certain properties and, consequently, the problem can be reduced to a convex formulation. However, these required properties correspond to very unlikely events in wireless/wireline networks, and therefore the method has a very limited applicability.

1.3 Local Methods for WSRMax in Wireless Networks

The worst case computational complexity for solving the general WSR-Max problem by applying global optimization approaches can increase more than polynomially with the number of variables. As a result, these methods are prohibitively expensive, even for off line optimization of moderate size networks. Therefore, the problem of WSRMax deserves efficient algorithms, which even though suboptimal, perform well in practice.

Several approximations have been proposed for the case when all links in the network operate in certain signal-to-interference-plus-noise ratio (SINR) regions. For example, the assumption that the achievable rate is a linear function of the SINR (i.e., low SINR region) is widely used in the ultra-wide-band systems, e.g., [98]. Other references, which provide solutions for the power and rate control in low SINR regions include [37, 69, 99]. The high SINR region is treated in [29, 58, 86]. However, at the optimal operating point different links correspond to different SINR regions, which is usually the case with multihop networks. Therefore, all methods mentioned above that are based on either the low or the high SINR assumptions can fail to solve the general problem.

One promising method is to cast the WSRMax problem into a signomial program (SP) formulation [20, sec. 9] or into a complementary geometric program (CGP) [6, 30], where a suboptimal solution can be obtained efficiently; we can readily convert an SP to a CGP and vice versa [30, sec. 2.2.5]. Applications of SP and CGP, or closely related solution methods, have been demonstrated in various signal processing and digital communications problems, e.g., [30, 31, 34, 35, 78, 94, 122, 127]. There are a number of other important papers proposing suboptimal solution methods for the WSRMax problem, such as [2, 27, 33, 45, 68, 70, 74, 105, 111, 116, 131, 151], among others.

Though the suboptimal methods mentioned above, including SP/CGP based algorithms, can perform reasonably well in many cases,[2] it is worth pointing out that not all of them can handle the general WSRMax problem. The reason is the self-interference problem, which arises when a node transmits and receives simultaneously in the same frequency band. Since there is a huge imbalance between the transmitted signal power and the received signal power of nodes, the transmitted signal strength is typically few orders of magnitude larger than the received signal strength. Thus, when a node transmits and receives simultaneously in the same channel, the useful signal at the receiver of the incoming link is overwhelmed by the transmitted signal of the node itself. As a result, the SINR values at the incoming link of a node that simultaneously transmits in the same channel is very small. Therefore, the self-interference problem plays a central role in WSRMax in general wireless networks [133].

Thus, in the case of general multihop wireless networks, the WSRMax problem must also cope with the self-interference problem. Under such circumstances SP/CGP cannot be directly applicable even to obtain a better suboptimal solution, since initialization of the algorithms is critical. One approach to dealing with self interference consists of adding supplementary combinatorial constraints, which prevent any node in the network from transmitting and receiving simultaneously [13, 14, 24, 38, 46, 61, 71, 138]. This is sometimes called the node-exclusive interference model; only subsets of mutually exclusive links can simultaneously be activated in order to avoid the large self interference encountered if a node transmits and receives in the same frequency band. Of course, such approaches induce a combinatorial nature for the WSRMax problem in general. The combinatorial nature is circumvented in [134], where *homotopy methods* (or continuation methods) [4] together with complementary geometric programming [6] are adopted to derive efficient algorithms for the general WSRMax

[2] For example, when a node does not transmits and receives simultaneously in the same frequency band.

problem. Here, the term "efficient" can mean faster convergence, or convergence to a point with better objective value.

1.4 Distributed WSRMax in Wireless Networks

The emergence of large scale communication networks, as well as accompanying network control and optimization methods with huge signalling overheads triggered a considerable body of recent research on developing distributed algorithms for resource management, see [21, 79, 141] and the references therein. Such distributed algorithms rely only on local observations and are carried out with limited access to global information. These algorithms essentially involve coordinating many local subproblems to find a solution to a large global problem. It is worth emphasizing that the convexity of the problems is crucial in determining the behavior of the distributed algorithms [21, chap. 9]. For example, in the case of nonconvex problems such algorithms need not converge, and if they do converge, they need not converge to an optimal point, which is the case with the WSRMax problem. Nevertheless, finding even a suboptimal yet distributed method is crucial for deploying distributively many network control and optimization methods, e.g., [41, 68, 81, 83, 84, 105, 118, 120, 138], which rely on WSRMax.

Distributed implementation of the WSRMax problem has been investigated in [27, 93, 94, 127, 144] in the context of digital subscriber loops (DSL) networks. Those systems are inherently consisting of single-input and single-output (SISO) links. Related algorithms for SISO wireless ad hoc networks and SISO orthogonal frequency division multiple access cellular systems are found in [53, 117, 147, 146]. However, in the case of multi antenna cellular systems, the decision variables space is, of course, larger, for example, joint optimization of transmit beamforming patterns, transmit powers, and link activations is required. Therefore, designing efficient distributed methods for WSRMax is a more challenging task due to the extensive amount of message passing required to resolve the coupling between variables. In the sequel, we limit ourselves to basic, but still very important, results that develop distributed coordinated algorithms for resource management in networks with multiple antennas.

Several distributed methods for WSRMax in multiple-input and single-output (MISO) cellular networks have been proposed in [10, 11, 72, 95, 130, 132, 136]. Specifically, in [95] a two-user MISO interference channel (IC)[3] is considered and a distributed algorithm is derived by using the commonly used high SINR approximation [29]. Moreover, another approximation, which relies on zero forcing (ZF) beamforming is introduced in [95] to address the problem in the case of multiuser MISO IC.

The methods proposed in [10, 11, 130] derived the necessary (but not sufficient) optimality conditions for the WSRMax problem and used it as the basis for their distributed solution. However, many parameters must be selected heuristically to construct a potential distributed solution and there is, in general no systematic method for finding those parameters. In particular, the algorithms in [10, 11] are designed for systems with very limited backhaul signaling resources and do not consider any iterative base station (BS) coordination mechanism to resolve the out-of-cell interference coupling. Even though the method proposed in [130] relies on stringent requirements on the message passing between BSs during each iteration of the algorithm, their results show that BS coordination can provide considerable gains compared to uncoordinated methods. An inexact cooperate descent algorithm for the case where each BS is serving only one cell edge user has been proposed in [72]. The method proposed in [66] is designed for sum-rate maximization and uses high SINR approximation. A cooperative beamforming algorithm is proposed in [152] for MISO IC, where each BS can transmit only to a single user. Their proposed method employs an iterative BS coordination mechanism to resolve the out-of-cell interference coupling. However, the convexity properties exploited for distribution of the problem are destroyed when more than one user is served by any BS. Thus, their proposed method is not directly applicable to the WSRMax problem. Recently, an interesting distributed algorithm for WSRMax is proposed by Shi et al. [110], which exploits a nontrivial equivalence between the WSRMax problem and a weighted sum mean

[3] K-user MISO IC means that there are K transmitter–receiver pairs, where the transmitters have multiple antennas and the receivers have single antennas.

squared error minimization problem. This algorithm relies on user terminal assistance, such as signal covariance estimations, computation and feedback of certain parameters form user terminals to BSs over the *air interface*. In practice, performing perfect covariance estimation and perfect feedback during each iteration can be very challenging. In the presence of user terminal imperfections, such as estimation and feedback errors, the algorithms performance can degrade and its convergence can be less predictable.

Algorithms based on game theory are found in [49, 55, 65, 107, 108, 109]. Their proposed methods are restricted to interference channels, for example, MISO IC, MIMO IC. The methods often require the coordination between receiver nodes and the transmitter nodes during algorithm's iterations.

Many optimization criteria other than the weighted sum-rate have been considered in references [12, 113, 123, 143, 148, 149, 150] to distributively optimize the system resources (e.g., beamforming patterns, transmit powers, etc.) in multi antenna cellular networks. In particular, the references [12, 148, 149, 150] used the characterization of the Pareto boundary of the MISO interference channel [56] as the basis for their distributed methods. Their proposed methods do not employ any BS coordination mechanism to resolve the out-of-cell interference coupling. In [113, 123, 143] distributed algorithms have been derived to minimize a total (weighted) transmitted power or the maximum per antenna power across the BSs subject to SINR constraints at the user terminals.

1.5 Outline of the Volume

Section 2 presents a solution method, based on the branch and bound technique, which solves globally the nonconvex WSRMax problem with an optimality certificate. Efficient analytic bounding techniques are introduced and their impact on convergence is numerically evaluated. The considered link-interference model is general enough to model a wide range of network topologies with various node capabilities, for example, single- or multipacket transmission (or reception), simultaneous transmission and reception. Diverse application domains of WSRMax are considered in the numerical results, including cross-layer network utility maximization and maximum weighted link scheduling for multihop wireless networks, as well as finding achievable rate regions for singlecast/multicast wireless networks.

Section 3 presents fast suboptimal algorithms for the WSRMax problem in multicommodity, multichannel wireless networks. First, the case where all receivers perform singleuser detection[4] is considered and algorithms are derived by applying complementary geometric programming and homotopy methods. Here we apply the algorithms within a general cross-layer utility maximization framework to examine quantitative impact of gains that can be achieved at the network layer in terms of end-to-end rates and network congestion. In addition, we show, through examples, that the algorithms are well suited for evaluating the gains achievable at the network layer when the network nodes employ self interference cancelation techniques with different degrees of accuracy. Finally, a case where all receivers perform multiuser detection is considered and solutions are presented by imposing additional constraints, such as that only one node can transmit to others at a time or that only one node can receive from others at a time.

Section 4 presents an easy to implement distributed method for the WSRMax problem in a multicell multiple antenna downlink system. The algorithm is based on primal decomposition and subgradient methods, where the original nonconvex problem is split into a master problem and a number of subproblems (one for each base station). A sequential convex approximation strategy is used to address the nonconvex master problem. Unlike the recently proposed minimum weighted mean-squared error based algorithms, the method presented here *does not* rely on any user terminal assistance. Only base station to base station synchronized signalling via backhaul links. All the necessary computation is performed at the BSs. Numerical experiments

[4] That is, a receiver decodes each of its intended signals by treating all other interfering signals as noise.

are provided to examine the behavior of the algorithm under different degrees of BS coordination.

Finally, in Section 5, we present our conclusions. The detailed work presented in this volume is based on the research performed by the authors that led to several recent journal and conference publications.

References

[1] I. C. Abou-Faycal, M. D. Trott, and S. Shamai, "The capacity of discrete-time memoryless Rayleigh-fading channels," *IEEE Transaction on Information Theory*, vol. 47, no. 4, pp. 1290–1301, May 2001.

[2] R. Agarwal and J. M. Cioffi, "Beamforming design for the MIMO downlink for maximizing weighted sum-rate," in *Proceedings on IEEE International Symposium on Information Theory and its Applications*, pp. 1–6, Auckland, New Zealand, December 7–10 2008.

[3] H. Al-Shatri and T. Weber, "Optimizing power allocation in interference channels using D.C. programming," in *Proceedings on Workshop on Resource Allocation in Wireless Networking*, pp. 367–373, Avignon, France, June 4 2010.

[4] E. L. Allgower and K. Georg, *Introduction to Numerical Continuation Methods*. Philadelphia, PA: SIAM, 2003.

[5] C. Audet, P. Hansen, and G. Savard, *Essays and Surveys in Global Optimization*. 233 Spring street, NY 10013, USA: Springer Science + Business Media, Inc, 2005.

[6] M. Avriel and A. C. Williams, "Complementary geometric programming," *SIAM Journal on Appllied Mathematics*, vol. 19, no. 1, pp. 125–141, July 1970.

[7] C. Bae and D. Cho, "Fairness-aware adaptive resource allocation scheme in multihop OFDMA systems," *IEEE Communications Letters*, vol. 11, no. 2, pp. 134–136, February 2007.

[8] V. Balakrishnan, S. Boyd, and S. Balemi, "Branch and bound algorithm for computing the minimum stability degree of parameter-dependent linear systems," *International Journal on Robust and Nonlinear Control*, vol. 1, no. 4, pp. 295–317, October–December 1991.

[9] D. E. Barreto and S. S. Chiu, "Decomposition methods for cross-layer optimization in wireless networks," in *Proceedings on IEEE Wireless Communications and Networking Conference*, pp. 270–275, Kawloon, Hong Kong, March 11–15 2007.

[10] E. Björnson, M. Bengtsson, and B. Ottersten, "Optimality properties and low-complexity solutions to coordinated multicell transmission," in *Proceedings on IEEE Global Telecommunications Confernce*, pp. 1–6, Miami, Florida, USA, December 6–10 2010.

[11] E. Björnson, N. Jaldén, M. Bengtsson, and B. Ottersten, "Optimality properties, distributed strategies, and measurement-based evaluation of coordinated multicell OFDMA transmission," *IEEE Transactions on Signal Processing*, vol. 59, no. 12, pp. 6086–6101, December 2011.

[12] E. Björnson, R. Zakhour, D. Gesbert, and B. Ottersten, "Cooperative multicell precoding: Rate region characterization and distributed strategies with instantaneous and statistical CSI," *IEEE Transactions on Signal Processing*, vol. 58, no. 8, pp. 4298–4310, August 2010.

[13] S. A. Borbash and A. Ephremides, "The feasibility of matchings in a wireless network," *IEEE Transactions on Information Theory*, vol. 52, no. 6, pp. 2749–2755, June 2006.

[14] S. A. Borbash and A. Ephremides, "Wireless link scheduling with power control and SINR constraints," *IEEE Transactions on Information Theory*, vol. 52, no. 11, pp. 5106–5111, November 2006.

[15] S. Boyd, "GGPLAB: A simple matlab toolbox for geometric programming," [Online]. Available: http://www.stanford.edu/~boyd/ggplab/, 2006.

[16] S. Boyd, "Branch-and-bound methods," [Online]. Available: http://www.stanford.edu/class/ee364b/lectures/bb_slides.pdf, 2007.

[17] S. Boyd, "Primal and dual decomposition," [Online]. Available: http://www.stanford.edu/class/ee364b/lectures/decomposition_slides.pdf, 2007.

[18] S. Boyd, "Sequential convex programming," [Online]. Available: http://www.stanford.edu/class/ee364b/lectures/seq_slides.pdf, 2007.

[19] S. Boyd, "Subgradient methods," [Online]. Available: http://www.stanford.edu/class/ee364b/lectures/subgrad_method_slides.pdf, 2007.

[20] S. Boyd, S. J. Kim, L. Vandenberghe, and A. Hassibi, "A tutorial on geometric programming," *Optimization and Engineering*, vol. 8, no. 1, pp. 67–127, 2007.

[21] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," *Foundations and Trends in Machine Learning*, vol. 3, no. 1, pp. 1–122, 2010.

[22] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, UK: Cambridge University Press, 2004.

[23] S. Boyd and L. Vandenberghe, "Additional exercises for convex optimization," [Online]. Available: http://www.stanford.edu/~boyd/cvxbook/bv_cvxbook_extra_exercises.pdf, May 2010.

[24] L. Bui, A. Eryilmaz, R. Srikant, and X. Wu, "Asynchronous congestion control in multi-hop wireless networks with maximal matching-based scheduling," *IEEE/ACM Transactions on Networking*, vol. 16, no. 4, pp. 826–839, August 2008.

[25] M. Cao, V. Raghunathan, S. Hanly, V. Sharma, and P. R. Kumar, "Power control and transmission scheduling for network utility maximization in wireless networks," in *Proceedings on IEEE International Conference on Decision and Control*, pp. 5215–5221, New Orleans, LA, USA, December 12–14 2007.

[26] M. Cao, X. Wang, S. Kim, and M. Madihian, "Multi-hop wireless backhaul networks: A cross-layer design paradigm," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 4, pp. 738–748, May 2007.

[27] R. Cendrillon, J. Huang, M. Chiang, and M. Moonen, "Autonomous spectrum balancing for digital subscriber lines," *IEEE Transactions on Signal Processing*, vol. 55, no. 8, pp. 4241–4257, August 2007.

[28] R. Cendrillon, W. Yu, M. Moonen, J. Verlinden, and T. Bostoen, "Optimal multiuser spectrum balancing for digital subscriber lines," *IEEE Transactions on Communications*, vol. 54, no. 5, pp. 922–933, May 2006.

[29] M. Chiang, "Balancing transport and physical layers in wireless multihop networks: Jointly optimal congestion control and power control," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 1, pp. 104–116, January 2005.

[30] M. Chiang, "Geometric programming for communication systems," vol. 2, no. 1-2, pp. 1–154, July 2005.

[31] M. Chiang, C. W. Tan, D. P. Palomar, D. O'Neill, and D. Julian, "Power control by geometric programming," *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 2640–2651, July 2007.

[32] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings on ACM International Conference on Mobile Computing and Networking*, pp. 1–12, Chicago, Illinois, USA, September 20–24 2010.

[33] S. S. Christensen, R. Agarwal, E. Carvalho, and J. Cioffi, "Weighted sum-rate maximization using weighted MMSE for MIMO-BC beamforming design," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 4792–4799, December 2008.

[34] M. Codreanu, "Multidimensional adaptive radio links for broadband communications," Ph.D. thesis, Centre for Wireless Communications, University of Oulu, Oulu, Finland: Acta Universitatis Ouluensis, [Online]. Available: http://herkules.oulu.fi/isbn9789514286223, November 2007.

[35] M. Codreanu, A. Tölli, M. Juntti, and M. Latva-aho, "Joint design of Tx-Rx beamformers in MIMO downlink channel," *IEEE Transactions on Signal Processing*, vol. 55, no. 9, pp. 4639–4655, September 2007.

[36] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. New York, USA: John Wiley, second Edition, 2006.

[37] R. L. Cruz and A. V. Santhanam, "Optimal routing, link scheduling and power control in multi-hop wireless networks," in *Proceedings on IEEE INFOCOM*, vol. 1, pp. 702–711, San Diego, CA, April 2003.

[38] T. ElBatt and A. Ephremides, "Joint scheduling and power control for wireless ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 3, no. 1, pp. 74–85, January 2004.

[39] K. Eriksson, "Dynamic resource allocation in wireless networks," Examensarbete utfört i Kommunikationssystem vid Tekniska högskolan i Linköping, [Online]. Available: http://liu.diva-portal.org/smash/get/diva2:326290/FULLTEXT01, 2010.

[40] A. Eryilmaz and R. Srikant, "Fair resource allocation in wireless networks using queue-length-based scheduling and congestion control," *IEEE/ACM Transactions on Networking*, vol. 15, no. 6, pp. 1333–1344, December 2007.

[41] A. Eryilmaz, R. Srikant, and J. R. Perkins, "Stable scheduling policies for fading wireless channels," *IEEE/ACM Transactions on Networking*, vol. 13, no. 2, pp. 411–424, April 2005.

[42] A. V. Fiacco, *Introduction to Sensitivity and Stability Analysis in Nonlinear Programming*, vol. 165. 111 Fifth Avenue, New York, New York 10003: Academic Press, Inc., 1983.

[43] L. Georgiadis, M. J. Neely, and L. Tassiulas, "Resource allocation and cross-layer control in wireless networks," *Foundations and Trends in Networks*, vol. 1, no. 1, pp. 1–144, April 2006.

[44] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, March 2000.

[45] C. Guthy, W. Utschick, R. Hunger, and M. Joham, "Efficient weighted sum rate maximization with linear precoding," *IEEE Transactions on Signal Processing*, vol. 58, no. 4, pp. 2284–2297, April 2010.

[46] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," *IEEE Transactions on Information Theory*, vol. 34, no. 5, pp. 910–917, September 1988.

[47] D. Halperin, T. Anderson, and D. Wetherall, "Taking the sting out of carrier sense: Interference cancellation for wireless LANs," in *Proceedings on ACM International conference on Mobile Computing and Networking*, pp. 339–350, San Francisco, California, USA, September 14–19 2008.

[48] S. V. Hanly and D. N. C. Tse, "Multiaccess fading channels — Part II: Delay-limited capacities," *IEEE Transactions on Information Theory*, vol. 44, no. 7, pp. 2816–2831, November 1998.

[49] Z. K. M. Ho and D. Gesbert, "Balancing egoism and altruism on the MIMO interference channel," *IEEE Journal on Selected Areas in Communications, submitted*, 2010, [Online]. Available: http://arxiv.org/PS_cache/arxiv/pdf/0910/0910.1688v1.pdf.

[50] L. M. C. Hoo, B. Halder, J. Tellado, and M. Cioffi, "Multi user transmit optimization for multiuser broadcast channels: Asymptotic fdma capacity region and algorithms," *IEEE Transactions on Communications*, vol. 52, no. 6, pp. 922–930, June 2004.

[51] R. A. Horn and C. R. Johnson, *Topics in Matrix Analysis*. Cambridge, UK: Cambridge University Press, 1994.

[52] R. Horst, P. Pardolos, and N. Thoai, *Introdiction to Global Optimization*, vol. 48. Dordrecht, Boston, London: Kluwer Academic Publishers, second Edition, 2000.

[53] J. Huang, R. Berry, and M. Honig, "Distributed interference compensation for wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 5, pp. 1074–1084, May 2006.

[54] J. Jang and K. B. Lee, "Transmit power adaptation for multiuser OFDM systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 2, pp. 171–178, February 2003.

[55] E. A. Jorswieck and E. G. Larsson, "The MISO interference channel from a game-theoretic perspective: A combination of selfishness and altruism achieves pareto optimality," in *Proceedings on IEEE International Conference on Acoustics, Speech, Signal Processing*, pp. 5364–5367, Las Vegas, Nevada, USA, March 31–April 4 2008.

[56] E. A. Jorswieck, E. G. Larsson, and D. Danev, "Complete characterization of the pareto boundary for the MISO interference channel," *IEEE Transactions on Signal Processing*, vol. 56, no. 10, pp. 5292–5296, October 2008.

[57] S. Joshi, P. C. Weeraddana, M. Codreanu, and M. Latva-aho, "Weighted Sum-Rate Maximization for MISO Downlink Cellular Networks via Branch and Bound," *IEEE Transactions on Signal Processing*, vol. 60, no. 4, pp. 2090–2095, April 2012.

[58] D. Julian, M. Chiang, D. ONeil, and S. Boyd, "QoS and fairness constrained convex optimization of resource allocation for wireless cellular and ad-hoc networks," in *Proceedings on IEEE INFOCOM*, vol. 2, pp. 477–486, New York, USA, June 2002.

[59] F. P. Kelly, "Charging and rate control for elastic traffic," *European Transactions on Telecommunications*, vol. 8, pp. 33–37, 1997.

[60] F. P. Kelly, A. Maulloo, and D. Tan, "Rate control for communication networks: Shadow prices, proportional fairness, and stability," *Journal of the Operations Research Society*, vol. 49, pp. 237–252, 1998.

[61] T. S. Kim, Y. Yang, J. C. Hou, and S. V. Krishnamurthy, "Joint resource allocation and admission control in wireless mesh networks," in *Proceedings on Int. Symp. on Modelling and Opt. in Mobile, Ad-hoc and Wireless Networks*, pp. 1–10, Seoul, Korea, June 23–27 2009.

[62] M. Kodialam and T. Nandagopal, "Characterizing achievable rates in multi-hop wireless mesh networks with orthogonal channels," *IEEE/ACM Transactions on Networking*, vol. 13, no. 4, pp. 868–880, August 2005.

[63] M. Kojima, N. Megiddo, and T. Noma, "Homotopy continuation methods for nonlinear complementarity problems," *Mathematics of Operational Research*, vol. 16, pp. 754–774, 1989.

[64] A. Kumar, D. Manjunath, and J. Kuri, *Wireless Networking*. Burlington, MA, USA: Elsevier Inc., 2008.

[65] E. G. Larsson and E. A. Jorswieck, "Competition Versus Cooperation on the MISO Interference Channel," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 7, pp. 1059–1069, September 2008.

[66] B. O. Lee, H. W. Je, I. Sohn, O.-S. Shin, and K. B. Lee, "Interference-aware decentralized precoding for multicell MIMO TDD systems," in *Proceedings on IEEE Global Telecommunications Conference*, pp. 1–5, New Orleans, LA, USA, November 30–December 4 2008.

[67] G. Li and H. Liu, "On the Optimality of the OFDMA networks," *IEEE Communications Letters*, vol. 9, no. 5, pp. 438–440, May 2005.

[68] X. Lin and N. B. Shroff, "Joint rate control and scheduling in multihop wireless networks," Technical Reports, Purdue University, [Online]. Available: http://cobweb.ecn.purdue.edu/~linx/papers.html, 2004.

[69] X. Lin and N. B. Shroff, "Joint rate control and scheduling in multihop wireless networks," in *Proceedings on IEEE International Conference on Decision and Control*, vol. 5, pp. 1484–1489, Atlantis, Paradise Island, Bahamas, December 14–17 2004.

[70] X. Lin and N. B. Shroff, "The impact of imperfect scheduling on cross-layer rate control in wireless networks," in *Proceedings on IEEE INFOCOM*, vol. 3, pp. 1804–1814, Miami, USA, March 13–17 2005.

[71] X. Lin, N. B. Shroff, and R. Srikant, "A tutorial on cross-layer optimization in wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1452–1463, August 2006.

[72] Y.-F. Liu, Y.-H. Dai, and Z.-Q. Luo, "Coordinated beamforming for MISO interference channel: Complexity analysis and efficient algorithms," *IEEE Transactions on Signal Processing*, vol. 59, no. 3, pp. 1142–1157, March 2011.

[73] M. S. Lobo, L. Vandenberghe, S. Boyd, and H. Lebret, "Applications of second-order cone programming," *Linear Algebra and Applications*, vol. 284, pp. 193–228, November 1998.

[74] R. Lui and W. Yu, "Low-complexity near-optimal spectrum balancing for digital subscriber lines," in *Proceedings on IEEE International Conference on Communications*, pp. 1947–1951, Seoul, Korea, May 16–20 2005.

[75] Z. Luo and S. Zhang, "Dynamic spectrum management: Complexity and duality," *IEEE Journal on Selected Areas in Communications*, vol. 2, no. 1, pp. 57–73, February 2008.

[76] Z. Q. Luo and W. Yu, "An introduction to convex optimization for communications and signal processing," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1426–1438, August 2006.

[77] B. R. Marks and G. P. Wright, "A general inner approximation algorithm for nonconvex mathematical programs," *Operational Research*, vol. 26, no. 4, pp. 681–683, July–August 1978.

[78] E. Matskani, N. D. Sidiropoulos, and L. Tassiulas, "Convex approximation algorithms for back-pressure power control of wireless multi-hop networks," in *Proceedings on IEEE International Conference on Acoustics, Speech, Signal Processing*, pp. 3032–3035, Prague, Czech Republic, May 22–27 2011.

[79] A. Nedić and A. Ozdaglar, "Cooperative distributed multi-agent optimization," in *Convex Optimization in Signal Processing and Communications*, (D. P. Palomar and Y. C. Eldar, eds.), pp. 340–386, Cambridge University Press, 2011.

[80] M. J. Neely, "Dynamic power allocation and routing for satellite and wireless networks with time varying channels," PhD thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, 2003.

[81] M. J. Neely, *Stochastic Network Optimization with Application to Communication and Queueing Systems*, vol. 7 of *Synthesis Lectures on Communication Networks.* San Rafael, CA: Morgan & Claypool, 2010.

[82] M. J. Neely, E. Modiano, and C. Li, "Fairness and optimal stochastic control for heterogeneous networks," *IEEE/ACM Transactions on Networking*, vol. 16, no. 2, pp. 396–409, April 2008.

[83] M. J. Neely, E. Modiano, and C. E. Rohrs, "Power allocation and routing in multibeam satellites with time-varying channels," *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 138–152, February 2003.

[84] M. J. Neely, E. Modiano, and C. E. Rohrs, "Dynamic power allocation and routing for time varying wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 1, pp. 89–103, January 2005.

[85] Y. Nesterov and A. Nemirovsky, *Interior-Point Polynomial Algorithms in Convex Programming.* SIAM, 1994.

[86] D. C. Oneill, D. Julian, and S. Boyd, "Optimal routes and flows in congestion constrained ad-hoc networks," in *Proceedings on IEEE Vehicle Technology Conference*, pp. 702–711, Los Angeles, CA, September 26–29 2004.

[87] D. P. Palomar, "A unified framework for communications through MIMO channels," PhD thesis, Department of Signal Theory and Communications, Technical University of Catalonia, Barcelona, Spain, May 2003.

[88] D. P. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 8, pp. 1439–1451, August 2006.

[89] D. P. Palomar and M. Chiang, "Alternative distributed algorithms for network utility maximization: Framework and applications," *IEEE Transactions on Automatic Control*, vol. 52, no. 12, pp. 2254–2269, December 2007.

[90] A. Pantelidou and A. Ephremides, "A cross-layer view of wireless multicasting under uncertainty," in *Proceedings on IEEE Information Theory Workshop*, pp. 110–114, Volos, Greece, June 10–12 2009.

[91] A. Pantelidou and A. Ephremides, "A cross-layer view of optimal scheduling," *IEEE Transactions on Information Theory*, vol. 56, no. 11, pp. 5568–5580, November 2010.

[92] C. H. Papadimitriou and K. Steiglitz, *Combinatorial Optimization: Algorithms and Complexity.* Englewood Cliffs NJ: Prentice-Hall, 1982.

[93] J. Papandriopoulos and J. S. Evans, "SCALE: A low-complexity distributed protocol for spectrum balancing in multiuser DSL networks," *IEEE Transactions on Information Theory*, vol. 55, no. 8, pp. 3711–3724, August 2009.

[94] J. Papandriopoulos and S. Evans, "Low-complexity distributed algorithms for spectrum balancing in multi-user DSL networks," in *Proceedings on IEEE International Conference on Communications*, pp. 3270–3275, Istanbul, Turkey, June 11–15 2006.

[95] S.-H. Park, H. Park, and I. Lee, "Distributed beamforming techniques for weighted sum-rate maximization in MISO interference channels," *IEEE Communications Letters*, vol. 14, no. 12, pp. 1131–1133, December 2010.

[96] N. T. H. Phuong and H. Tuy, *A Unified Monotonic Approach to Generalized Linear Fractional Programming.* Kluwer Academic Publishers, 2003.

[97] L. Qian, Y. J. A. Zhang, and J. Huang, "MAPEL: Achieving global optimality for a non-convex wireless power control problem," *IEEE Transactions on Wireless Communications*, vol. 8, no. 3, pp. 1553–1563, March 2009.

[98] B. Radunovic and J. L. Boudec, "Optimal power control, scheduling, and routing in UWB networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 7, pp. 1252–1270, September 2004.

[99] B. Radunovic and J. L. Boudec, "Power Control is not Required for Wireless Networks in the Linear Regime," in *Proceedings on IEEE International Symposium World of Wireless, Mobile and Multiple Networks*, vol. 5, pp. 417–427, Taormina, Giardini Naxos, Italy, June 13–16 2005.

[100] B. Radunović, D. Gunawardena, P. Key, A. Proutiere, N. Singh, V. Balan, and G. Dejean, "Rethinking Indoor Wireless: Low Power, Low Frequency, Full-duplex," Technical Reports MSR-TR-2009-148, Microsoft Research, July 2009, [Online]. Available: http://research.microsoft.com/apps/pubs/default.aspx?id=104950.

[101] B. Radunović, D. Gunawardena, P. Key, A. Proutiere, N. Singh, V. Balan, and G. Dejean, "Rethinking indoor wireless mesh design: Low power, low frequency, full-duplex," in *Proceedings on IEEE Works on Wireless Mesh Networks*, pp. 1–6, Boston, USA, June 21 2010.

[102] B. Radunović, D. Gunawardena, A. Proutiere, N. Singh, V. Balan, and P. Key, "Efficiency and fairness in distributed wireless networks through self-interference cancellation and scheduling," Technical Reports MSR-TR-2009-27, Microsoft Research, [Online]. Available: http://research.microsoft.com/apps/pubs/default.aspx?id=79933, March 2009.

[103] W. Rudin, *Principles of Mathematical Analysis*. USA: McGraw-Hill, Inc., 3 Edition, 1976.

[104] K. Seong, M. Mohseni, and M. Cioffi, "Optimal resource allocation for OFDMA downlink systems," in *Proceedings on IEEE International Symposium on Information Theory*, pp. 1394–1398, Seattle, USA, July 9–14 2006.

[105] G. Sharma, R. R. Mazumdar, and N. B. Shroff, "On the complexity of scheduling in wireless networks," in *Proceedings on ACM International Conference on Mobile Computation and Networking*, pp. 227–238, Los Angeles, CA, USA, September 24–29 2006.

[106] Z. Shen, J. G. Andrews, and B. L. Evans, "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *IEEE Transactions on Wireless Communications*, vol. 4, no. 6, pp. 2726–2737, November 2005.

[107] C. Shi, R. A. Berry, and M. L. Honig, "Distributed interference pricing with MISO channels," in *Proceedings on Annual Allerton Conference Communications, Cont, Computing*, pp. 539–546, Urbana-Champaign, USA, September 23–26 2008.

[108] C. Shi, R. A. Berry, and M. L. Honig, "Monotonic convergence of distributed interference pricing in wireless networks," in *Proceedings on IEEE International Symposium on Information Theory*, pp. 1619–1623, Seoul, Korea, June 28–July 3 2009.

[109] C. Shi, R. A. Berry, and M. L. Honig, "Local interference pricing for distributed beamforming in MIMO networks," in *Proceedings on IEEE Military Communications Conference*, pp. 1–6, Boston, MA, October 18–21 2009.

[110] Q. Shi, M. Razaviyayn, Z.-Q. Luo, and C. He, “An iteratively weighted MMSE approach to distributed sum-utility maximization for a MIMO interfering broadcast channel,” *IEEE Transactions on Signal Processing*, vol. 59, no. 9, pp. 4331–4340, September 2011.

[111] S. Shi, M. Schubert, and H. Boche, “Weighted sum-rate optimization for multiuser MIMO systems,” in *Proceedings of the Conference on Information Sciences Systems (CISS)*, pp. 425–430, Baltimore, MD, USA, March 14–16 2007.

[112] Y. Shi and Y. T. Hou, “A distributed optimization algorithm for multi-hop cognitive radio networks,” in *Proceedings on IEEE INFOCOM*, pp. 1292–1300, Phoenix, AZ, USA, April 13–18 2008.

[113] B. Song, R. L. Cruz, and B. D. Rao, “A simple joint beamforming and power control algorithm for multi-user MIMO wireless networks,” in *Proceedings on IEEE Vehicles Technology Conference*, pp. 247–251, Los Angeles, CA, September 26–29 2004.

[114] B. Song, R. L. Cruz, and B. D. Rao, “Network duality and its application to multi-user MIMO wireless networks with SINR constraints,” in *Proceedings on IEEE International Conference on Communications*, vol 4, pp. 2684–2689, Seoul, Korea, May 16–20 2005.

[115] T. Starr, M. Sorbara, J. Cioffi, and P. J. Silverman, *DSL Advances*. Upper Saddle River, NJ 07458: Prentice-Hall, 2003.

[116] M. Stojnic, H. Vikalo, and B. Hassibi, “Rate maximization in multi-antenna broadcast channels with linear preprocessing,” *IEEE Transactions on Wireless Communications*, vol. 5, no. 9, pp. 2338–2342, September 2006.

[117] A. Stolyar and H. Viswanathan, “Self-organizing dynamic fractional frequency reuse for best-effort traffic through distributed inter-cell coordination,” in *Proceedings on IEEE INFOCOM*, pp. 1287–1295, Rio De Janeiro, Brazil, April 19–25 2009.

[118] A. L. Stolyar, “Maximizing queueing network utility subject to stability: Greedy primal-dual algorithm,” *Queing Systems*, vol. 50, no. 4, pp. 401–457, August 2005.

[119] H. Suzuki, K. Itoh, Y. Ebin, and M. Sato, “A booster configuration with adaptive reduction of transmitter-receiver antenna coupling for pager systems,” in *Proceedings on IEEE Vehicles Technology Conference* , vol. 3, pp. 1516–1520, Amsterdam, Netherlands, September 19–22 1999.

[120] L. Tassiulas and A. Ephremides, “Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks,” *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936–1949, December 1992.

[121] 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, March 1993.

[122] A. Tölli, M. Codreanu, and M. Juntti, “Cooperative MIMO-OFDM cellular system with soft handover between distributed base station antennas,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1428–1440, April 2008.

[123] A. Tölli, H. Pennanen, and P. Komulainen, "Decentralized minimum power multi-cell beamforming with limited backhaul signaling," *IEEE Transactions on Wireless Communications*, vol. 10, no. 2, pp. 570–580, February 2011.

[124] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, UK: Cambridge University Press, 2005.

[125] D. N. Tse, "Optimal power allocation over parallel gaussian broadcast channels," *Unpublished, a short summary published in Proceedings of International Symposium on Information Theory, Ulm, Germany*, 1997.

[126] D. N. C. Tse and S. V. Hanly, "Multiaccess fading channels. I. Polymatroid structure, optimal resource allocation and throughput capacities," *IEEE Transactions on Information Theory*, vol. 44, no. 7, pp. 2796–2815, November 1998.

[127] P. Tsiaflakis, M. Diehl, and M. Moonen, "Distributed spectrum management algorithms for multiuser DSL networks," *IEEE Transactions on Signal Processing*, vol. 56, no. 10, pp. 4825–4843, October 2008.

[128] P. Tsiaflakis, W. Tan, Y. Yi, M. Chiang, and M. Moonen, "Optimality certificate of dynamic spectrum management in multi-carrier interference channels," in *Proceedings on IEEE International Symposium on Information Theory*, pp. 1298–1302, Toronto, Canada, July 6–11 2008.

[129] P. Tsiaflakis, J. Vangorp, M. Moonen, and J. Verlinden, "A low complexity optimal spectrum balancing algorithm for digital subscriber lines," *Elseviser Signal Processing*, vol. 87, no. 7, July 2007.

[130] L. Venturino, N. Prasad, and X. Wang, "Coordinated linear beamforming in downlink multi-cell wireless networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 4, pp. 1451–1461, April 2010.

[131] N. Vucic, S. Shi, and M. Schubert, "DC programming approach for resource allocation in wireless networks," in *Proceedings on Workshop on Resource Allocation in Wireless Networking*, pp. 360–366, Avignon, France, June 4 2010.

[132] P. C. Weeraddana, M. Codreanu, and M. Latva-aho, "Multicell downlink weighted sum-rate maximization: A distributed approach," in *Proceedings on Annual Asilomar Conference on Signals, Systems and Computers, to appear*, Pacific Grove, CA, USA, November 6–9 2011.

[133] P. C. Weeraddana, M. Codreanu, M. Latva-aho, and A. Ephremides, "On the effect of self-interference cancelation in multihop wireless networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, Article ID 513952, 10 pages, 2010, doi:10.1155/2010/513952.

[134] P. C. Weeraddana, M. Codreanu, M. Latva-aho, and A. Ephremides, "Resource allocation for cross-layer utility maximization in wireless networks," *IEEE Transactions on Vehicles Technology*, vol. 60, no. 6, pp. 2790–2809, July 2011.

[135] P. C. Weeraddana, M. Codreanu, M. Latva-aho, and A. Ephremides, "Weighted sum-rate maximization for a set of interfering links via branch and bound," *IEEE Transactions on Signal Processing*, vol. 59, no. 8, pp. 3977–3996, August 2011.

[136] P. C. Weeraddana, M. Codreanu, M. Latva-aho, and A. Ephremides, "Multicell downlink weighted sum-rate maximization: A distributed approach," *IEEE Transactions on Signal Processing, submitted*, 2012.

[137] H. Weingarten, Y. Steinberg, and S. Shamai, "The capacity region of the Gaussian multiple-input multiple-output broadcast channel," *IEEE Transactions on Information Theory*, vol. 52, no. 9, pp. 3936–3964, September 2006.

[138] X. Wu and R. Srikant, "Regulated maximal matching: A distributed scheduling algorithm for multi-hop wireless networks with node-exclusive spectrum sharing," in *Proceedings on IEEE Conference on Decision and Control, and the European Control Conference*, pp. 5342–5347, Seville, Spain, December 12–15 2005.

[139] Y. Xu, T. Le-Ngoc, and S. Panigrahi, "Global concave minimization for optimal spectrum balancing in multi-user DSL networks," *IEEE Transactions on Signal Processing*, vol. 56, no. 7, pp. 2875–2885, July 2008.

[140] Y. Xu, S. Panigrahi, and T. Le-Ngoc, "A concave minimization approach to dynamic spectrum management for digital subscriber lines," in *Proceedings on IEEE International Conference on Communications*, pp. 84–89, Istanbul, Turkey, June 11–15 2006.

[141] B. Yang and M. Johansson, "Distributed optimization and games: A tutorial overview," *Networked Control Systems, Lecture Notes in Control and Information Sciences, London: Springer-Verlag*, vol. 406, pp. 109–148, 2011.

[142] Y. Yi and M. Chiang, "Stochastic network utility maximization: A tribute to Kelly's paper published in this journal a decade ago," *European Transactions on Telecommunications*, vol. 19, no. 4, pp. 421–442, June 2008.

[143] H. D. W. Yu, "Coordinated beamforming for the multicell multi-antenna wireless system," *IEEE Transactions on Wireless Communications*, vol. 9, no. 5, pp. 1748–1759, May 2010.

[144] W. Yu, "Multiuser water-filling in the presence of crosstalk," San Diego, USA, pp. 414–420, January 29–February 2, 2007.

[145] W. Yu and M. Cioffi, "FDMA capacity of Gaussian multiple-access channels with ISI," *IEEE Transactions on Communications*, vol. 50, no. 1, pp. 102–111, January 2002.

[146] W. Yu, T. Kwon, and C. Shin, "Joint scheduling and dynamic power spectrum optimization for wireless multicell networks," in *Proceedings on Conference on Information Sciences Systems (CISS)*, pp. 1–6, Princeton, NJ, USA, March 21–23 2010.

[147] J. Yuan and W. Yu, "Distributed cross-layer optimization of wireless sensor networks: A game theoretic approach," in *Proceedings on IEEE Global Telecommunications Conference*, San Francisco, California, November 27–December 1 2006.

[148] R. Zakhour and D. Gesbert, "Coordination on the MISO interference channel using the virtual SINR framework," in *Proceedings on ITG Workshop Smart Antennas*, Berlin, Germany, February 16–18 2009.

[149] R. Zakhour and D. Gesbert, "Distributed multicell-MISO precoding using the layered virtual SINR framework," *IEEE Transactions on Wireless Communications*, vol. 9, no. 8, pp. 2444–2448, August 2010.

[150] R. Zakhour, Z. Ho, and D. Gesbert, "Distributed beamforming coordination in multicell MIMO channels," in *Proceedings on IEEE Vehicles Technology Conference*, pp. 1–5, Barcelona, Spain, April 26–29 2009.
[151] L. Zhang, Y. Xin, Y. C. Liang, and H. V. Poor, "Cognitive multiple access channels: Optimal power allocation for weighted sum rate maximization," *IEEE Transactions on Communications*, vol. 57, no. 9, pp. 2754–2762, September 2009.
[152] R. Zhang and S. Cui, "Cooperative interference management with MISO beamforming," *IEEE Transactions on Signal Processing*, vol. 58, no. 10, pp. 5450–5458, October 2010.