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Algorithms and Techniques

10th International Workshop, APPROX 2007
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Preface

This volume contains the papers presented at the 10th International Workshop on Approximation Algorithms for Combinatorial Optimization Problems (APPROX 2007) and the 11th International Workshop on Randomization and Computation (RANDOM 2007), which took place concurrently at Princeton University, on August 20–22, 2007. APPROX focuses on algorithmic and complexity issues surrounding the development of efficient approximate solutions to computationally difficult problems, and this was the 10th in the series after Aalborg (1998), Berkeley (1999), Saarbrücken (2000), Berkeley (2001), Rome (2002), Princeton (2003), Cambridge (2004), Berkeley (2005), and Barcelona (2006). RANDOM is concerned with applications of randomness to computational and combinatorial problems, and this was the 11th workshop in the series following Bologna (1997), Barcelona (1998), Berkeley (1999), Geneva (2000), Berkeley (2001), Harvard (2002), Princeton (2003), Cambridge (2004), Berkeley (2005), and Barcelona (2006).

Topics of interest for APPROX and RANDOM are: design and analysis of approximation algorithms, hardness of approximation, small space and data streaming algorithms, sub-linear time algorithms, embeddings and metric space methods, mathematical programming methods, coloring and partitioning, cuts and connectivity, geometric problems, game theory and applications, network design and routing, packing and covering, scheduling, design and analysis of randomized algorithms, randomized complexity theory, pseudorandomness and derandomization, random combinatorial structures, random walks/Markov chains, expander graphs and randomness extractors, probabilistic proof systems, random projections and embeddings, error-correcting codes, average-case analysis, property testing, computational learning theory, and other applications of approximation and randomness.

The volume contains 21 contributed papers, selected by the APPROX Program Committee out of 49 submissions, and 23 contributed papers, selected by the RANDOM Program Committee out of 50 submissions.

We would like to thank all of the authors who submitted papers and the members of the Program Committees:

APPROX 2007

Nikhil Bansal, IBM T J Watson
Moses Charikar, Princeton University (chair)
Chandra Chekuri, University of Illinois, Urbana-Champaign
Julia Chuzhoy, IAS
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August 2007

Moses Charikar and Omer Reingold, Program Chairs
Klaus Jansen and José D. P. Rolim, Workshop Chairs

Table of Contents

Contributed Talks of APPROX

Contributed Talks of RANDOM

Approximation Algorithms and Hardness for Domination with Propagation

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Abstract. The power dominating set (PDS) problem is the following extension of the well-known dominating set problem: find a smallest-size set of nodes S that power dominates all the nodes, where a node v is power dominated if (1) v is in S or v has a neighbor in S, or (2) v has a neighbor w such that w and all of its neighbors except v are power dominated. Note that rule (1) is the same as for the dominating set problem, and that rule (2) is a type of propagation rule that applies iteratively. We use n to denote the number of nodes. We show a hardness of approximation threshold of $2^{\log^{1-\epsilon} n}$ in contrast to the logarithmic hardness for dominating set. This is the first result separating these two problem. We give an $O(\sqrt{n})$ approximation algorithm for planar graphs, and show that our methods cannot improve on this approximation guarantee. We introduce an extension of PDS called ℓ-round PDS; for $\ell = 1$ this is the dominating set problem, and for $\ell \geq n-1$ this is the PDS problem. Our hardness threshold for PDS also holds for ℓ-round PDS for all $\ell \geq 4$. We give a PTAS for the ℓ-round PDS problem on planar graphs, for $\ell = O(\frac{\log n}{\log \log n})$. We study variants of the greedy algorithm, which is known to work well on covering problems, and show that the approximation guarantees can be $\Theta(n)$, even on planar graphs. Finally, we initiate the study of PDS on directed graphs, and show the same hardness threshold of $2^{\log^{1-\epsilon} n}$ for directed acyclic graphs.

Keywords: Approximation Algorithms, Hardness of Approximation, PTAS, Dominating Set, Power Dominating Set, Planar Graphs, Integer Programming, Greedy Algorithms.

1 Introduction

A Dominating Set of an (undirected) graph $G = (V, E)$ is a set of nodes S such that every node in the graph is in S or has a neighbor in S. The problem of finding a dominating set of minimum size is an important problem that has been extensively studied, especially in the last twenty years, see the books by Haynes et al. [16,17]. Our focus is on an extension called the Power Dominating Set

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(abbreviated as PDS) problem. Power domination is defined by two rules; the first rule is the same as for the DOMINATING SET problem, but the second rule allows a type of indirect propagation. More precisely, given a set of nodes S, the set of nodes that are *power dominated* by S, denoted $\mathcal{P}(S)$, is obtained as follows

(Rule 1) if node v is in S, then v and all of its neighbors are in $\mathcal{P}(S)$;
(Rule 2) (propagation) if node v is in $\mathcal{P}(S)$, one of its neighbors w is not in $\mathcal{P}(S)$, and all other neighbors of v are in $\mathcal{P}(S)$, then w is inserted into $\mathcal{P}(S)$.

It can be seen that the set $\mathcal{P}(S)$ is independent of the sequence in which nodes are inserted into $\mathcal{P}(S)$ by Rule 2. The PDS problem is to find a node-set S of minimum size that power dominates all the nodes (i.e., find $S \subseteq V$ with $|S|$ minimum such that $\mathcal{P}(S) = V$). We use $\texttt{Opt}(G)$ to denote the size of an optimal solution for graph G. We use n to denote $|V(G)|$, the number of nodes in the input graph.

For example, consider the planar graph in Figure 1; the graph has t disjoint triangles, and three (mutually disjoint) paths such that each path has exactly one node from each triangle; note that $|V| = 3t$. The minimum dominating set has size $\Theta(|V|)$, since the maximum degree is 4. The minimum power dominating set has size one – if S has any one node of the innermost (first) triangle (like v), then $\mathcal{P}(S) = V$[1].

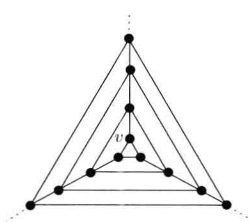

Fig. 1. Example for PDS

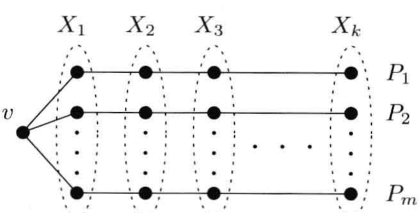

Fig. 2. Example for ℓ-round PDS

The PDS problem arose in the context of the monitoring of electric power networks. A power network contains a set of nodes and a set of edges connecting the nodes. A power network also contains a set of *generators*, which supply power, and a set of *loads*, where the power is directed to. In order to monitor a power network

[1] In more detail, we apply Rule 1 to see that all the nodes of the innermost (first) triangle and one node of the second triangle are in $\mathcal{P}(S)$; then by two applications of Rule 2 (to each of the nodes in the first triangle not in S), we see that the other two nodes of the second triangle are in $\mathcal{P}(S)$; then by three applications of Rule 2 (to each of the nodes in the second triangle) we see that all three nodes of the third triangle are in $\mathcal{P}(S)$; etc.

we need to measure all the state variables of the network by placing measurement devices. A Phasor Measurement Unit (PMU) is a measurement device placed on a node that has the ability to measure the voltage of the node and the current phase of the edges connected to the node; PMUs are expensive devices. The goal is to install the minimum number of PMUs such that the whole system can be monitored. These units have the capability of monitoring remote elements via propagation (as in Rule 2); see Brueni [8], Baldwin et al. [5], and Mili et al. [24]. Most measurement systems require one measurement device per node, but this does not apply to PMUs; hence, PMUs give a huge advantage. To see this in more detail consider a power network $G = (V, E)$, and assume that the resistances of the edges in the power network are known, and the goal is to measure the voltages of all nodes. For simplicity, assume that there are no generators and loads. By placing a PMU at node v we can measure the voltage of v and the electrical current on each edge incident to v. Next, by using Ohm's law we can compute the voltage of any node in the neighborhood of v (Rule 1). Now assume that the voltage on v and all of its neighbors except w is known. By applying ohm's law we can compute the current on the edges incident to v except $\{v, w\}$. Next by using Kirchhoff's law we compute the current on the edge $\{v, w\}$. Finally, applying Ohm's law on the edge $\{v, w\}$ gives us the voltage of w (Rule 2).

PMUs are used to monitor large system stability and to give warnings of system-wide failures. PMUs have become increasingly popular for monitoring power networks, and have been installed by several electricity companies since 1988 [23,6]. For example, the USA Western States Coordinating Council (WSCC) had installed around 34 PMUs by 1999 [6]. By now, several hundred PMUs have been installed world wide [26]. Some researchers in electrical engineering regard PMUs as the most important device for the future of power systems [25].

Our motivation comes from the area of approximation algorithms and hardness results. The DOMINATING SET problem is a so-called *covering problem*; we wish to cover all the nodes of the graph by choosing as few node neighborhoods as possible. In fact, the DOMINATING SET problem is a special case of the well-known SET COVERING[2] problem. Such covering problems have been extensively investigated. One of the key positive results dates from the 1970's, when Johnson [18] and Lovász [21] showed that the greedy method achieves an approximation guarantee of $O(\log n)$ where n denotes the size of the ground set.

Several negative results (on the hardness of approximation) have been discovered over the last few years: Lund and Yannakakis [22] showed that SET COVERING is hard to approximate within a ratio of $\Omega(\log n)$, modulo some variants of the $\mathsf{P} \neq \mathsf{NP}$ assumption. Later, Feige [12] showed that SET COVERING is hard to approximate within $(1 - \epsilon) \ln n$, modulo some variants of the $\mathsf{P} \neq \mathsf{NP}$ assumption. A natural question is what happens to covering problems (in the setting of approximation algorithms and hardness results) when we augment the covering rule with a propagation rule. PDS seems to be a key problem of this

[2] Given a family of sets on a groundset, find the minimum number of sets whose union equals the groundset.

type, since it is obtained from the DOMINATING SET problem by adding a simple propagation rule.

Previous literature: Apparently, the earliest theoretical publications on PDS are Brueni [8], Baldwin et al. [5], Mili set al. [24]. Later, Haynes et al. [15] showed that the problem is NP-complete even when the input graph is bipartite; they presented a linear-time algorithm to solve PDS optimally on trees. Kneis et al. [19] generalized this result to a linear-time algorithm that finds an optimal solution for graphs that have bounded tree-width, relying on earlier results of Courcelle et al. [10]. Kneis et al. [19] also showed that PDS is a generalization of DOMINATING SET. Guo et al. [14] developed a combinatorial algorithm based on dynamic programming for optimally solving PDS on graphs with bounded tree-width in linear-time. Even for planar graphs, the DOMINATING SET problem is NP-hard [13], and the same holds for PDS [14]. Brueni and Heath [9] have more results on PDS, including the NP-completeness of PDS on planar bipartite graphs.

Our contributions: Our results substantially improve on the understanding of PDS in the context of approximation algorithms.

- For general graphs, we show that PDS cannot be approximated better than $2^{\log^{1-\epsilon} n}$, unless $\mathsf{NP} \subseteq \mathsf{DTIME}(n^{polylog(n)})$. This is a substantial improvement over the previous logarithmic hardness result. This seems to be the first known "separation" result between PDS and DOMINATING SET.
- We introduce an extension of PDS called the ℓ-round PDS problem by adding a parameter ℓ to PDS which restricts the number of "parallel" rounds of propagation that can be applied (see Section 3.2 for formal definitions). The rules are the same as PDS, except we apply the propagation rule in parallel, in contrast to PDS where we apply the propagation rule sequentially. This problem has applications to monitoring power networks when there is a time constraint that should be met; deducing information through a parallel round of propagation takes one unit of time and in some applications we want to detect a failure in the network after at most ℓ units of time. Moreover, the ℓ-round PDS problem has theoretical significance because it allows one to study the spectrum of problems between DOMINATING SET and PDS, and see how the hardness threshold changes as we change the ℓ parameter. We show that ℓ-round PDS for $\ell \geq 4$ cannot be approximated better than $2^{\log^{1-\epsilon} n}$, unless $\mathsf{NP} \subseteq \mathsf{DTIME}(n^{polylog(n)})$.
- We focus on planar graphs, and give a PTAS for ℓ-round PDS for $\ell = O(\frac{\log n}{\log\log n})$. Baker's PTAS [4] for the DOMINATING SET problem on planar graphs is a special case of our result with $\ell = 1$, and no similar result of this type was previously known for $\ell > 1$. Note that the ℓ-round PDS problem remains NP-hard on planar graphs (for all $\ell \geq 1$). Also, note that our PTAS does not apply to PDS in general, because the running time is super-polynomial for $\ell = \omega(\frac{\log n}{\log\log n})$.
- We introduce the notion of strong regions and weak regions as a means of obtaining lower bounds on the size of an optimal solution for PDS. Based on