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Abstract. The optimization problem of measuring all nodes in an electrical network by placing as few measurement units (PMUs) as possible is known as Power Dominating Set. Nodes can be measured indirectly according to Kirchhoff's law. We show that this problem can be solved in linear time for graphs of bounded treewidth and establish bounds on its parameterized complexity if the number of PMUs is the parameter.

1 Introduction

Electrical networks can be interpreted as undirected graphs in a very natural fashion. Each node represents a measuring point and edges denote electrical connections between them. In this paper, we discuss a graph problem known as Power Dominating Set which has been introduced by Haynes, Hedetniemi, Hedetniemi and Henning [12]. In order to observe the voltage and phase angle at some measuring point, we may place a Phase Measurement Unit (PMU) on it, and by a law resembling Kirchhoff's current law, we can observe measuring points indirectly as well. More precisely, we have the following rules that tell us how nodes and edges can be measured:

1. A PMU on a node v observes v, all incident edges, and all adjacent nodes.
2. If a vertex v of degree $d \geq 2$ is incident to $d-1$ observed edges, *all* edges of v are observed.
3. If an edge $e = \{v, w\}$ is observed, v und w are observed as well.
4. If two adjacent nodes v and w are observed, the edge $\{v, w\}$ is observed as well.

The Power Dominating Set problem is defined by the following question: Given an undirected graph $G = (V, E)$ and a nonnegative integer k, is there a subset $M \subseteq V$ with $|M| \leq k$ such that all nodes from V would be observed according to the four rules, if we placed a PMU on every $v \in M$?

Power Dominating Set is similar to the well-known problem Dominating Set. In this, we look for a dominating set D of k nodes, such that every node either is an element of D or has a neighbor in D. Dominating set is itself a classical NP-complete problem [10]. What makes Power Dominating Set seemingly harder to solve is its non-local structure: For dominating set the placement of a dominating node cannot influence other parts in the graph that are far away, while this is perfectly possible for Power Dominating Set. A path of arbitrary length, for example, can be measured by a single PMU at one of its ends.

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It is well known that Dominating Set can be solved efficiently for graphs of bounded treewidth [15]. Graphs of treewidth k are also called partial k-trees. The notion of treewidth was introduced by Robertson and Seymour [14] and measures how treelike a graph is. Bodlaender [2] and Kloks [13] give an introduction to this concept. Many graph problems that are hard in general can be efficiently solved, i.e. in polynomial and often linear time, for graphs of bounded treewidth, e.g., Hamiltonian Path, Max-Cut, Independent Set and Vertex Cover [15]. A notable exception is bandwidth minimization [9].

Because of its non-local structure, standard techniques do not easily lead to efficient algorithms for Power Dominating Set even for graphs of bounded treewidth. The first polynomial algorithm for Power Dominating Set works only on trees, i.e., on graphs with treewidth one [12]. Haynes et al. left the generalization to bounded treewidth as an open question. A small step in this direction is a new algorithm by Guo, Hüffner and Niedermeier [11] that solves Power Dominating Set in polynomial time for trees with a constant number of additional edges. This class of graphs is a subset of all graphs with bounded treewidth, but does not even contain all graphs with treewidth two; E.g., a $2 \times n$–grid has treewidth two, but is a tree with $n - 1$ additional edges.

In what follows, we achieve the general result that Power Dominating Set can be solved in linear time for any fixed treewidth k, thereby solving the open problem posed in the article that incited research in this area [12].

Parameterized Complexity

In parameterized complexity every input instance has an associated natural number, called the *parameter*. Often, the parameter is part of the input, otherwise it is a — usually simple — function of the input. The time complexity of a parameterized problem is measured as a function in both the input length n and the parameter k. We say that a problem is *fixed parameter tractable* or in the complexity class FPT if there is an algorithm that can solve the problem in $f(k)n^c$ steps, where c is a constant and f is an arbitrary function. The idea behind parameterized complexity theory is that hard problems can be easy in practice if hard instances do not occur. The parameter measures how hard an instance is and the complexity "explodes" only in terms of the parameter. See the influential monograph by Downey and Fellows [7] for an introduction to parameterized complexity.

We can parameterize Power Dominating Set in several reasonable ways. Two natural parameterers are the treewidth of the graph and the number of needed PMUs.

Let k be the treewidth of a graph. If we had two algorithms that solve Power Dominating Set in n^k resp. $k^k n^3$ steps, both would imply that the problem can be solved in polynomial time for graphs of bounded treewidth, i.e., all graphs whose treewidth is bounded by some constant. The second, but not the first algorithm would also imply that Power Dominating Set is fixed parameter tractable. Please note that the second algorithm is still feasible if k has a moderate value, but the first becomes impractical for even small values of k. Hence, parameterized complexity makes a better statement than simply "polynomial for fixed k."

In this sense Guo, Hüffner and Niedermeier showed that Power Dominating Set is fixed parameter tractable if the number of edges added to a tree is the parameter.

In conventional complexity there is the class P of efficiently solvable problems, as well as NP, whose complete problems are unlikely to be in P. In parameterized complexity, these are paralleled by FPT as opposed to $W[1], W[2], \ldots, W[P]$ whose complete problems are unlikely to be fixed parameter tractable. It is known that Dominating Set is W[2]-complete if the size of the dominating set is the parameter [8]. We show in this paper that Power Dominating Set is in W[P] and is W[2]-hard if the number of PMUs is the parameter. Unfortunately, we cannot establish the complexity exactly, but there are many problems with W[2] as a lower and W[P] as an upper bound. Examples are Longest Common Subsequence [3], Maximal Irredundant Set [4] and Monochrome Cycle Cover [7].

2 A Simplified Set of Rules

To begin with, we found a way to simplify the problem description by using a smaller set of rules equivalent to the four original rules mentioned above. The idea is to measure edges implicitly so that we only need to make sure that all nodes are observed. This can be achieved by adjusting the first, contracting the second and third, and omitting the fourth rule.

Lemma 1. *The following set of rules is equivalent to the original set of rules with respect to observed nodes:*

1. *A PMU on a node v observes v and all its neighbors.*
2. *If an observed vertex v of degree $d \geq 2$ is adjacent to $d-1$ observed nodes,* all *its neighbors are observed.*

Proof. To see that the contraction of the second and third original rule into the new second one does not change the possibilities to observe nodes, let us return to the original set of rules. There is no rule that creates an observed edge both of whose nodes are not observed. Only the second rule is capable of creating an observed edge exactly one of whose nodes is not observed. By the third rule, however, this node becomes observed immediately.

Thus, by applying the third rule immediately each time we apply the second one, we contract these two rules into one. It then never happens that an observed edge is incident to a node that is not yet observed. Thus, we do not have to consider observed edges any longer, and the modification of the first rule as well as the deletion of the fourth rule are clearly uncritical. □

3 Fixed-Treewidth Tractability

In this section, we apply a theorem by Courcelle et al. [6, Theorem 27] to show that *Power Dominating Set* can be solved in linear time for graphs of bounded treewidth.

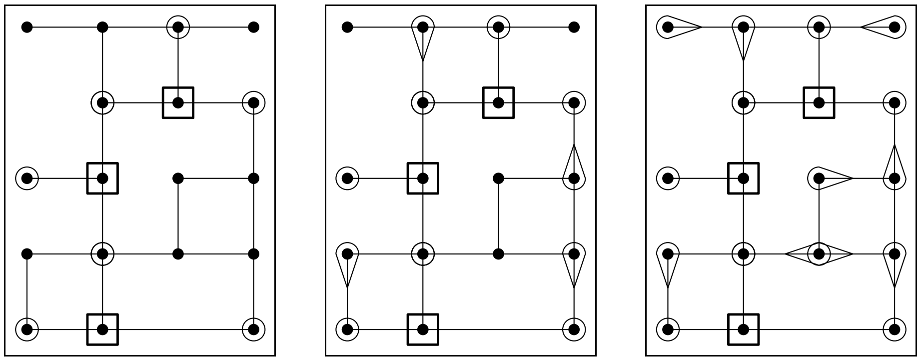

Fig. 1. A graph that is power-dominated by three PMUs. Nodes with PMUs are marked by a square, and neighbors of such nodes are marked by a circle. All these vertices are observed according to the first rule. Nodes observed due to the Kirchhoff rule are marked by a comet whose tail points at the induction source.

Proposition 1 (Courcelle et al.).
Let p and k be fixed integers. Every $\mathrm{LinEMSOL}(\tau_{1,p})$ *optimization problem on the class of partial k-trees can be solved in $O(V)$ time and the corresponding algorithm can be derived constructively from its* $\mathrm{LinEMSOL}(\tau_{1,p})$ *definition.*

$\mathrm{LinEMSOL}(\tau_{1,p})$ denotes monadic second order logic (MSO) with linear evaluation functions. To begin with, recall that monadic second order logic is an extension of first order logic that allows us to quantify over unary predicate variables (that is, subsets of the universe). The vocabulary τ_1 consists of a single binary relation E over $V \times V$ that encodes the edges of a given graph. Clearly, every graph G can be expressed as a τ_1-structure $\langle V, E \rangle$.

For any fixed integer p, the vocabulary $\tau_{1,p}$ is an extension of τ_1 that introduces p additional unary predicates $U_1, \ldots, U_p$ to the language (in so far, τ_1 can be interpreted as $\tau_{1,0}$). These extended vocabularies, however, are not going to be required in this section at all, hence we omit further details.

For a vocabulary τ, we say that a graph problem is an $\mathrm{MSO}(\tau)$ decision problem if it can be stated as a closed MSO formula over the vocabulary τ. $\mathrm{LinEMSOL}(\tau)$ optimization problems are a bit more complicated, and for the sake of brevity we only describe the very special and restricted kind of these problems that is relevant in our context. A graph problem is a $\mathrm{LinEMSOL}(\tau)$ optimization problem of this kind if it can be expressed as follows:

The input consists of a graph given as a τ-structure $G(\tau) = \langle V, E \rangle$ and an evaluation function $f \colon V \to \mathbf{N}$. There is a fixed $\mathrm{MSO}(\tau)$ formula θ that contains a free set variable X whose universe is V. The problem is to find a valuation of X that fulfills $\langle G(\tau), X \rangle \models \theta(X)$ at minimal cost with respect to f, that is,

$$\arg\min_{X \subseteq V} \Big\{ \sum_{x \in X} f(x) \ \Big| \ \langle G(\tau), X \rangle \models \theta(X) \Big\}.$$

In the general case, LinEMSOL optimization problems can be a lot more complex, even for the vocabulary τ_1 alone: there can be an arbitrary number of free set variables X_i, an arbitrary number of evaluation functions f_j, and fixed integer weights as coefficients for each $f_j(X_i)$.

Lemma 2. *Power Dominating Set can be expressed as an* LinEMSOL(τ_1) *optimization problem as follows:*

$$\arg\min_{X \subseteq V} |X| : \forall V_M \subseteq V.\ V_M = \mathit{observed\_nodes}(X) \rightarrow V_M = V$$

where

$$\mathit{observed\_nodes}(X) \equiv \{\, v \in V \mid \mathit{near\_PMU}(v) \vee \mathit{kirchhoff}(v) \,\}$$

$$\mathit{near\_PMU}(v) \equiv v \in X \vee \exists u \in X.\ \mathit{adj}(v, u)$$

$$\begin{aligned}\mathit{kirchhoff}(v) \equiv \exists w \in V_M.\ (\mathit{adj}(v, w)\ \wedge \\ \forall w' \in V.\ (\mathit{adj}(w', w) \rightarrow w' = v \vee w' \in V_M))\end{aligned}$$

Proof. It is easily verified that $\mathit{near\_PMU}(v)$ holds of a node v exactly if it is directly measured by a node in X via the first rule. As well, $\mathit{kirchhoff}(v)$ if and only if v is observed using the second rule. Note that V_M is constructed as a fixed point in a quasi iterative manner: If a node w and all of his neighbors save one have been measured (and thus are part of V_M), the last remaining neighbor is also observed, by the Kirchhoff rule.

Thus, we have that under the premise $V_M = \mathit{observed\_nodes}(X)$, exactly the measured nodes are contained in V_M. That way, the conclusion $V_M = V$ is satisfied if and only if the whole graph G is power-dominated by X. We achieve the smallest such X by the min optimization. □

Corollary 1. Power Dominating Set *is in* FPT *when we choose the treewidth of the input graph as the parameter.*

Notice that Proposition 1 allows for defining the integer-weighted version of the problem as well, where placing a PMU on a node v has cost $f(v)$. By omitting f in the above lemma, we implicitly assigned a weight of 1 to each node.

4 Hardness for W[2]

The most natural parameter for the Power Dominating Set problem may not be the treewidth, but the number of PMUs required to power-dominate the input graph. In this section, we show that Power Dominating Set is W[2]-hard for this parameterization. It is already known that Power Dominating Set is NP-complete, but the reduction from 3-SAT given by Haynes et al. [12] cannot be used to show W[2]-hardness. Therefore, we take a different approach.

Theorem 1. Power Dominating Set *is* W[2]-*hard when we choose the number of PMUs as the parameter.*

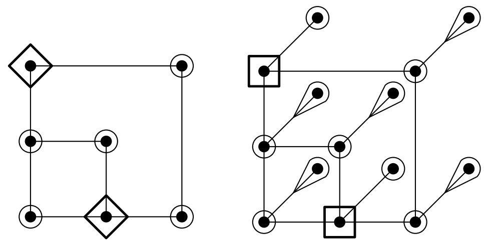

Fig. 2. A dominated graph and its corresponding power-dominated antenna graph. In the first graph, diamonds and circles denote dominators and dominated nodes, respectively. The nodes in the second graph are marked according to the notation used in Figure 1.

Proof. By reduction from Dominating Set, where the number of dominators is the parameter. This problem is W[2]-complete [8].

Given an input graph $G = (V, E)$ for Dominating Set, construct the graph $G' = (V', E')$ by copying G and adding a single edge with a new node v' to each node $v \in V$. Let us call such an egde $\{v, v'\}$ the *antenna of* v. We will now prove the following equality of the two domination numbers: G can be dominated by d nodes if and only if G' can be power-dominated by d nodes.

$\Rightarrow$: Let $D \subseteq V$ dominate G such that $|D|$ is minimal. Clearly, D also dominates all nodes in G' except for, maybe, nodes v' on antennae $\{v, v'\}$ for some nodes $v \in V$. As all neighbors of any such node v, except for v', are dominated by D, the Kirchhoff rule applies, and we have that D power-dominates the entire graph G'.

$\Leftarrow$: Let $D \subseteq V'$ power-dominate G' such that $|D|$ is minimal. If D uses the node v' of the antenna $\{v, v'\}$ for some $v \in V$, we may replace D by $D \cup \{v\}) - \{v'\}$ without losing the power domination property, as v is the only neighbor of v'. Since this operation does not change the size of D, we may assume that $D \subseteq V$ without loss of generality. It remains to show that the Kirchhoff rule never applies to any node from V, which means that D is also a dominating set for $G'[V]$ and thus for G.

Mark all nodes in D and all their neighbors, and assume there exists a node $v \in V$ that remains unmarked, which means that v is not dominated by D. The Kirchhoff rule can only be applied if v has a neighbor $w \in V$ all of whose neighbors but v are marked. As there is an antenna $\{w, w'\}$, w has a neighbor $w' \notin V$ that cannot be marked unless $w \in D$. However, if $w \in D$, then v (as a neighbor of w) must be marked. This contradicts choosing v as an unmarked node, showing that there is no node in $G'[V]$ not dominated by D. □

5 Containedness in W[P]

In the case that the number of PMUs is chosen as the parameter, Power Dominating Set is in W[P]. This follows directly from a result by Cai, Chen, Downey and Fellows [5]:

Proposition 2 (Cai, Chen, Downey, Fellows). *Let Q be a parameterized problem which is in NP as a classical problem. Then $Q \in W[P]$ if and only if there is a nondeterministic Turing machine M deciding Q such that, given* *the input (x, k), M performs at most $p(|x| + k)$ steps and at most $f(k) \cdot \log n$ nondeterministic steps (for some computable f and polynomial p).*

Corollary 2. Power Dominating Set $\in$ *W[P].*

Proof. A nondeterministic Turing machine can guess a set X of k node numbers (ranging from 1 through n) in $k \cdot \log n$ nondeterministic steps. It may then in deterministic polynomial time compute the set V_M of measured nodes under the assumption that exactly the nodes in X have PMUs, and finally check whether $V_M = V$. □

6 Summary

In this paper we studied the parameterized complexity of Power Dominating Set. We started out by simplifying the traditional rules used to describe the problem. Collecting the threads spun in earlier scholarship, we answered the hitherto open question as to the tractability of Power Dominating Set regarding treewidth as parameter in the positive.

Assuming another viewpoint, we showed that the problem becomes W[2]-hard when parameterized by the number of Phase Measurement Units instead of treewidth. However, this version is contained in W[P]. That leaves a more precise complexity characterization of Power Dominating Set, parameterized by the number of PMUs, as an interesting open question. To us, it seems reasonable that the inductive effect of the Kirchoff rule would make Power Dominating Set more difficult to solve than Dominating Set, possibly even as hard as Induced Formula Satisfiability, which has been shown to be W[P]-complete [1].

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