A Randomized Fully Polynomial Time Approximation Scheme for the All-Terminal Network Reliability Problem

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Abstract

The classic all-terminal network reliability problem posits a graph, each of whose edges fails independently with some given probability. The goal is to determine the probability that the network becomes disconnected due to edge failures. This problem has obvious applications in the design of communication networks. Since the problem is $\sharp\mathcal{P}$-complete and thus believed hard to solve exactly, a great deal of research has been devoted to *estimating* the failure probability. In this paper, we give a *fully polynomial randomized approximation scheme* that, given any n-vertex graph with specified failure probabilities, computes in time polynomial in n and $1/\epsilon$ an estimate for the failure probability that is accurate to within a relative error of $1 \pm \epsilon$ with high probability. We also give a deterministic polynomial approximation scheme for the case of small failure probabilities. Some extensions to evaluating probabilities of k-connectivity, strong connectivity in directed Eulerian graphs, and r-way disconnection, and to evaluating the Tutte polynomial are also described.

1 Introduction

1.1 The Problem

We consider a classic problem in reliability theory: given a network on n vertices, each of whose m links is assumed to fail (disappear) independently with some probability, determine the probability that the surviving network is connected. The practical applications of this question to communication networks are obvious, and the problem has therefore been the subject of a great deal of study. Coulbourn [4] provides a survey.

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Formally, a network is modeled as a graph G, each of whose edges e is presumed to fail (disappear) with some probability p_e and thus to survive with probability $q_e = 1 - p_e$. Network reliability problems are concerned with determining the probabilities of certain connectivity-related events in this network. The most basic question of *all-terminal network reliability* is determining the probability that the network stays connected. Others include determining the probability that two particular nodes stay connected (two-terminal reliability), and so on.

Most such problems, including the two just mentioned, are $\sharp\mathcal{P}$-complete [25, 24]. That is, they are universal for a complexity class at least as intractable as $\mathcal{NP}$ and therefore seem unlikely to have polynomial time solutions. Attention therefore turned to approximation algorithms. Provan and Ball [24] proved that it is $\sharp\mathcal{P}$-complete even to *approximate* the reliability of a network to within a relative error of ϵ. However, they posited that the approximation parameter ϵ is part of the input, and used an exponentially small ϵ (which can be represented in $O(n)$ input bits) to prove their claim. They note at the end of their article that "a seemingly more difficult unsolved problem involves the case where ϵ is constant, i.e. is not allowed to vary as part of the input list."

Their idea is formalized in the definition of a *polynomial approximation scheme* (PAS). In this definition, the performance measure is the running time of the approximation algorithm as a function of the problem size n and the error parameter ϵ, and the goal is for a running time that is polynomial in n for each fixed ϵ (e.g., $2^{1/\epsilon}n$). If the running time is also polynomial in $1/\epsilon$, the algorithm is called a *fully polynomial approximation scheme (FPAS)*. An alternative interpretation of an FPAS is that it has a running time polynomial in the input size when ϵ is constrained to be input in unary rather than binary notation. When randomization is used in an approximation scheme, we refer to a *polynomial randomized approximation scheme (PRAS)* or *fully polynomial randomized approximation scheme (FPRAS)*. Such algorithms are required to provide an ϵ-approximation with probability at least $3/4$; this probability of success can be increased significantly (e.g., to $1 - 1/n$ or even $1 - 1/2^n$) by repeating the algorithm a small number of times [23].

Deterministic FPASs for nontrivial problems seem to be quite rare. However, FPRASs have been given for several $\sharp\mathcal{P}$-complete problems such as counting maximum matchings in dense graphs [7], measuring the volume of a convex polytope [6], and *disjunctive normal form (DNF) counting*—estimating the probability that a given DNF formula evaluates to true if the variables are made true or false at random [18]. In a plenary talk, Kannan [8] raised the problem of network reliability as an important remaining open problems needing an approximation scheme.

1.2 Our Results

In this paper, we provide an FPRAS for the all-terminal network reliability problem. Given a failure probability p for the edges, our algorithm, in time polynomial in n and $1/\epsilon$, returns a number P that estimates the probability

FAIL(p) that the graph becomes disconnected. With high probability,[1] P is in the range $(1 \pm \epsilon)$FAIL(p). The algorithm is Monte Carlo, meaning that the approximation is correct with high probability but that it is not possible to verify its correctness. It generalizes to the case where the edge failure probabilities are different, to computing the probability the graph is not k-connected (for any fixed k), and to the more general problem of approximating the *Tutte Polynomial* for a large family of graphs. It can also estimate the probability that an *Eulerian directed* graph remains strongly connected under edge failures. Our algorithm is easy to implement and appears likely to have satisfactory time bounds in practice [3, 16].

Some care must be taken with the notion of approximation because approximations are measured by *relative* error. We therefore get different results depending on whether we discuss the failure probability FAIL(p) or the reliability (probability of remaining connected) REL(p) $= 1 -$ FAIL(p). Consider a graph with a very low failure probability, say ϵ. In such a graph, approximating REL(p) by 1 gives a $(1 + \epsilon)$-approximation to the reliability, but approximating the failure probability by 0 gives a very poor (infinite) approximation ratio for FAIL(p). Thus, the failure probability is the harder quantity to approximate well. On the other hand, in a very unreliable graph, FAIL(p) becomes easy to approximate (by 1) while REL(p) becomes the challenging quantity. Our algorithm is an FPRAS for FAIL(p). This means that in extremely unreliable graphs, it cannot approximate REL(p). However, it does solve the harder approximation problem on reliable graphs, which are clearly the ones likely to be encountered in practice.

The basic approach of our FPRAS is to consider two cases. When FAIL(p) is large, it can be estimated via direct Monte Carlo simulation of random edge failures. We thus focus on the case of small FAIL(p). Note that a graph becomes disconnected when all edges in some cut fail (a *cut* is a partition of the vertices into two groups; its edges are the ones with one endpoint in each group). The more edges cross a cut, the less likely it is that they will all fail simultaneously. We show that for small FAIL(p), only the smallest graph cuts have any significant chance of failing. We show that there is only a polynomial number of such cuts, and that they can be enumerated in polynomial time. We then use a *DNF counting* algorithm [17] to estimate the probability that one of these explicitly enumerated cuts fails, and take this estimate as an estimate of the overall graph failure probability.

After presenting our basic FPRAS for FAIL(p) in Section 2, we present several extensions of it, all relying on our observation regarding the number of small cuts a graph can have. In Section 3, we give FPRASs for the network failure probability when every edge has a different failure probability, for the probability that an Eulerian directed graph fails to be strongly connected under random edge failures, and for the probability that two particular "weakly connected" vertices are disconnected by random edge failures. In Section 4, we

[1] The phrase *with high probability* means that the probability that it does not happen can be made $O(n^{-d})$ for any desired constant d by suitable choice of other constants (typically hidden in the asymptotic notation).

give an FPRAS for the probability that a graph partitions into more than r pieces for any fixed r. In Section 5, we give two deterministic algorithms for all-terminal reliability: a simple heuristic that provably gives good approximations on certain inputs and a deterministic PAS that applies to a somewhat broader class of problems. In Section 6, we show that our techniques give an FPRAS for the Tutte Polynomial on almost all graphs.

1.3 Related Work

Previous work gave algorithms for estimating FAIL(p) in certain special cases. Karp and Luby [18] showed how to estimate FAIL(p) in n-vertex planar graphs when the expected number of edge failures is $O(\log n)$. Alon, Frieze, and Welsh [1] showed how to estimate it when the input graph is sufficiently dense (with minimum degree $\Omega(n)$). Other special case solutions are discussed in Colbourn's survey [4]. Lomonosov [21] independently derived some of the results presented here.

A crucial step in our algorithm is the enumeration of minimum and near-minimum cuts. Dinitz et al. [5] showed how to enumerate (and represent) all minimum cuts. Vazirani and Yannakakis [26] showed how to enumerate near-minimum cuts. Karger and Stein [15] and Karger [11] gave faster cut enumeration algorithms as well as bounds on the number of cuts that we will use heavily.

A preliminary version of this work appeared in [10]. The author's thesis [9] discusses reliability estimation in the context of a general approach to random sampling in optimization problems involving cuts. In particular, this reliability work relies on some new theorems bounding the number of small cuts in graphs; these theorems have led to other results on applications of random sampling to graph optimization problems [12, 11, 2].

2 The Basic FPRAS

In this section, we present an FPRAS for FAIL(p). We use two methods, depending on the value of FAIL(p).

When FAIL(p) is large we estimate it in polynomial time by direct Monte Carlo simulation of edge failures. That is, we randomly cause edge to fail and check whether the graph remains connected. Since FAIL(p) is large, a small number of simulations (roughly $1/\text{FAIL}(p)$) gives enough data to estimate it well.

When FAIL(p) is small, we resort to *cut enumeration* to estimate it. A graph becomes disconnected precisely when all of the edges in some cut of the graph fail. By a *cut* we mean a partition of the graph vertices into two groups. The *cut edges* are those with one endpoint in each group (we also refer to these edges as the ones *crossing* the cut). The *value* of the cut is the number of edges crossing the cut.

We show that when FAIL(p) is small, only cuts of small value in G have any significant chance of failing. We observe that there is only a polynomial number of such cuts and that they can be found in polynomial time. We therefore estimate FAIL(p) by enumerating the polynomial-size set of small cuts of G and then estimating the probability that one of them fails.

If each edge fails with probability p, then the probability that a k-edge cut fails is p^k. Thus, the smaller a cut, the more likely it is to fail. It is therefore natural to focus attention on the small graph cuts. Throughout this paper, we assume that our graph has *minimum cut* value c—that is, that the smallest cut in the graph has exactly c edges. Such a graph has a probability of at least p^c of becoming disconnected—namely, if the minimum cut fails. That is:

Fact 2.1. *If each edge of a graph with minimum cut c fails independently with probability p, then the probability that the graph becomes disconnected is at least p^c.*

The probability that a cut fails decreases exponentially with the number of edges in the cut. This would suggest that a graph is most likely to fail at its small cuts. We formalize this intuition.

Definition 2.2. An *α-minimum cut* is a cut with value at most α times the minimum cut value.

Below, we show how to choose between the two approaches just discussed. If $p^c \geq n^{-4}$ then, as we show in Section 2.1, we can estimate it via Monte Carlo simulation. This works because FAIL(p) $\geq p^c$, so $\tilde{O}(1/\text{FAIL}(p)) = \tilde{O}(n^4)$ experiments give us enough data to deduce a good estimate ($\tilde{O}(f)$ denotes $O(f \log n)$). On the other hand, when $p^c < n^{-4}$, we know that a given α-minimum cut fails with probability $p^{\alpha c} = n^{-4\alpha}$. We show in Section 2.2 that there are at most $n^{2\alpha}$ α-minimum cuts. It follows that the probability that *any* α-minimum cut fails is less than $n^{-2\alpha}$—that is, exponentially decreasing with α. Thus, for a relatively small α, the probability that a greater than α-minimum cut fails is negligible. Thus (as we show in Section 2.3) we can approximate FAIL(p) by approximating the probability that some less than α-minimum cut fails. Our FPRAS (in Section 2.4) is based on enumerating these small cuts and determining the probability that one of them fails.

2.1 Monte Carlo Simulation

The most obvious way to estimate FAIL(p) is through Monte Carlo simulations. Given the failure probability p for each edge, we can "simulate" edge failures by flipping an appropriately biased random coin for each edge. We can then test whether the resulting network is connected. If we do this many times, then the fraction of trials in which the network becomes disconnected should intuitively provide a good estimate of FAIL(p). Karp and Luby [18] investigated this idea formally, and observed (a generalization of) the following.

Theorem 2.3. *Performing $O((\log n)/(\epsilon^2 \text{FAIL}(p)))$ trials will give an estimate for FAIL(p) accurate to within $1 \pm \epsilon$ with high probability.*

Corollary 2.4. *If* $\mathrm{FAIL}(p) \geq p^c \geq n^{-4}$*, then* $\mathrm{FAIL}(p)$ *can be estimated to within* $(1+\epsilon)$ *in* $\tilde{O}(mn^4/\epsilon^2)$ *time using Monte Carlo simulation.*

The criterion that $\mathrm{FAIL}(p)$ not be too small can of course be replaced by a condition that implies it. For example, Alon, Frieze, and Welsh [1] showed that for any *constant* p, there is an FPRAS for network reliability in *dense* graphs (those with minimum degree $\Omega(n)$). The reason is that as n grows and p remains constant, $\mathrm{FAIL}(p)$ is bounded below by a constant on dense graphs and can therefore be estimated in $\tilde{O}(n^2/\epsilon^2)$ time by direct Monte Carlo simulation.

The flaw of the simulation approach is that it is too slow for small values of $\mathrm{FAIL}(p)$, namely those less than 1 over a polynomial in n. It is upon this situation that we focus our attention for the remainder of this section. In this case, a huge number of standard simulations would have to be run before we encountered a sufficiently large number of failures to estimate $\mathrm{FAIL}(p)$. (Note that we expect to run $1/\mathrm{FAIL}(p)$ trials before seeing *any* failures. With no failures, we have no way to measure a failure probability.) Karp and Luby [18] tackled this situation for various problems, and showed that it could be handled in some cases by biasing the simulation such that occurrences of the event being estimated became more likely. One of their results was an FPRAS for network reliability in *planar* graphs, under the assumption that the failure probability p of edges is $O((\log n)/n)$ so that the expected number of edges failing is $O(\log n)$. Their algorithm is more intricate than straightforward simulation, and, like ours, relies on identifying a small collection of "important cuts" on which to concentrate.

Another problem where direct Monte Carlo simulation breaks down, and to which Karp and Luby [18], found a solution, is that of *DNF counting*: given a boolean formula in disjunctive normal form (an "or" of "and"s), and given for each variable a probability that it is set to true, estimate the probability that the entire formula evaluates to true. Like estimating $\mathrm{FAIL}(p)$, this problem is hard when the probability being estimated is very small. Karp and Luby [18] developed an FPRAS for DNF counting using a biased Monte Carlo simulation. The running time was later improved by Karp, Luby, and Madras [17] to yield the following.

Theorem 2.5. *There is an FPRAS for the DNF counting problem that runs in* $\tilde{O}(s/\epsilon^2)$ *time on any size* s *formula.*

We will use the DNF counting algorithm as a subroutine in our FPRAS.

2.2 Counting Near-minimum Cuts

Having handled the case of p^c larger, we now turn to the case of p^c small. We show that in this case, only the smallest graph cuts have any significant chance of failure. While it is obvious that cuts with fewer edges are more likely to fail, one might think that there are so many large cuts that overall they are more likely to fail than the small cuts. However, the following proposition lets us bound the number of large cuts and show this is not the case.

Theorem 2.6. *An undirected graph has less than $n^{2\alpha}$ α-minimum cuts.*

Remark. Vazirani and Yannakakis [26] gave an incomparable bound on the number of small cuts by *rank* rather than by value.

In this section, we sketch a proof of Theorem 2.6. A detailed proof of the theorem can be found in [15] and an alternative proof in [11]. Here, we sketch enough detail to allow for some of the extensions we will need later. We prove the theorem only for unweighted multigraphs (graphs with parallel edges between the same endpoints); the theorem follows for weighted graphs if we replace any weight w edge by a set of w unweighted parallel edges.

2.2.1 Contraction

The proof of the theorem is based on the idea of *edge contraction*. Given a graph $G = (V, W)$ and an edge (v, w), we define a contracted graph $G/(v, w)$ with vertex set $V' = V \cup \{u\} - \{v, w\}$ for some new vertex u and edge set

$$E' = E - \{(v, w)\} \cup \{(u, x) \mid (v, x) \in E \text{ or } (w, x) \in E\}.$$

In other words, in the contracted graph, vertices v and w are replaced by a single vertex u, and all edges originally incident on v or w are replaced by edges incident on u. We also remove self-loops formed by edges parallel to the contracted edge since they cross no cut in the contracted graph.

Fact 2.7. *There is a one-to-one correspondence between cuts in G/e and cuts in G that e does not cross. Corresponding cuts have the same value.*

Proof. Consider a partition (A, B) of the vertices of $G/(v, w)$. The vertex u corresponding to contracted edge (v, w) is on one side or the other. Replacing u by v and w gives a partition of the vertices of G. The same edges cross the corresponding partitions. □

2.2.2 The Contraction Algorithm

We now use repeated edge contraction in an algorithm that selects a cut from G. Consider the following *Contraction Algorithm*. While G has more than 2 vertices, choose an edge e uniformly at random and set $G \leftarrow G/e$. When the algorithm terminates, we are left with a two-vertex graph that has a unique cut. A transitive application of Fact 2.7 shows that this cut corresponds to a unique cut in our original graph; we will say this cut is *chosen* by the Contraction Algorithm. We show that any particular minimum cut is chosen with probability at least n^{-2}. Since the choices of different cuts are disjoint events whose probabilities add up to one, it will follow that there are at most n^2 minimum cuts. We then generalize this argument to α-minimum cuts.

Lemma 2.8. *The Contraction Algorithm chooses any particular minimum cut with probability at least n^{-2}.*

Proof. Each time we contract an edge, we reduce the number of vertices in the graph by one. Consider the stage in which the graph has r vertices. Suppose G has minimum cut c. It must have minimum degree c, and thus at least $rc/2$ edges. Our particular minimum cut has c edges. Thus a randomly chosen edge is in the minimum cut with probability at most $c/(rc/2) = 2/r$. The probability that we never contract a minimum cut edge through all $n-2$ contractions is thus at least

$$\begin{aligned}
\left(1-\frac{2}{n}\right)\left(1-\frac{2}{n-1}\right)\cdots\left(1-\frac{2}{3}\right) &= \left(\frac{n-2}{n}\right)\left(\frac{n-3}{n-1}\right)\cdots\left(\frac{2}{4}\right)\left(\frac{1}{3}\right) \\
&= \frac{(n-2)(n-3)\cdots(3)(2)(1)}{n(n-1)(n-2)\cdots\cdots(4)(3)} \\
&= \frac{2}{n(n-1)} \\
&= \binom{n}{2}^{-1} \\
&> n^{-2}.
\end{aligned}$$

□

2.2.3 Proof of Theorem 2.6

We can extend the approach above to prove Theorem 2.6. We slightly modify the Contraction Algorithm and lower bound the probability that it chooses a particular α-minimum cut. With r vertices remaining, the probability we choose an edge from our particular α-minimum cut is at most $2\alpha/r$. Let $k = \lceil 2\alpha \rceil$. Suppose we perform random contractions until we have a k-vertex graph. In this graph, choose a vertex partition (cut) uniformly at random, so that each cut is chosen with probability 2^{1-k}. It follows that a particular α-minimum cut is chosen with probability

$$\begin{aligned}
(1-\frac{2\alpha}{n})(1-\frac{2\alpha}{(n-1)})\cdots(1-\frac{2\alpha}{k+1})2^{1-k} &= \frac{(n-2\alpha)!}{(k-2\alpha)!}\frac{k!}{n!}2^{1-k} \\
&= \frac{\binom{k}{2\alpha}}{\binom{n}{2\alpha}}2^{1-k} \\
&> n^{-2\alpha}.
\end{aligned}$$

Note that for α not a half-integer, we are making use of *generalized binomial coefficients* which may have non-integral arguments. These are discussed by Knuth [19, Sections 1.2.5–6] (cf. Exercise 1.2.6.45). There, the Gamma function is introduced to extend factorials to real numbers such that $\alpha! = \alpha(\alpha-1)!$ for all real $\alpha > 0$. Many standard binomial identities extend to generalized binomial coefficients, including the facts that $\binom{n}{2\alpha} < n^{2\alpha}/(2\alpha)!$ and $2^{2\alpha-1} \leq (2\alpha)!$ for $\alpha \geq 1$.

Remark. The Contraction Algorithm described above is used only to count cuts. An efficient *implementation* given by Karger and Stein [15] can be used to *find* all α-minimum cuts in $\tilde{O}(n^{2\alpha})$ time. We use this algorithm in our FPRAS.

2.3 Cut Failure Bounds

Using the cut counting theorem just given, we show that large cuts do not contribute significantly to a graph's failure probability. Consider Theorem 2.6; taking $\alpha = 1$, it follows from the union bound that the probability that some minimum cut fails is at most $n^2 p^c$. We now show that the probability that *any* cut fails is only a little bit larger.

Theorem 2.9. *Suppose a graph has minimum cut c and that each edge of the graph fails independently with probability p, where $p^c = n^{-(2+\delta)}$ for some $\delta > 0$. Then*

1. *The probability that the given graph disconnects is at most $n^{-\delta}(1 + 2/\delta)$, and*

2. *The probability that a cut of value αc or greater fails in the graph is at most $n^{-\alpha\delta}(1 + 2/\delta)$.*

Remark. We conjecture that a probability bound of $n^{-\alpha\delta}$ can be proven (eliminating the $(1 + 2/\delta)$ term).

Proof. We prove Part 1 and then note the small change needed to prove Part 2. For the graph to become disconnected, all the edges in some cut must fail. We therefore bound the failure probability by summing the probabilities that each cut fails. Let r be the number of cuts in the graph, and let $c_1, \ldots, c_r$ be the values of the r cuts in increasing order so that $c = c_1 \le c_2 \le \cdots \le c_r$. Let $p_k = p^{c_k}$ be the probability that all edges in the k^{th} cut fail. Then the probability that the graph disconnects is at most $\sum p_k$, which we proceed to bound from above.

We proceed in two steps. First, consider the first n^2 cuts in the ordering (they might not be minimum cuts). Each of them has $c_k \ge c$ and thus has $p_k \le n^{-(2+\delta)}$, so that

$$\sum_{k \le n^2} p_k \le (n^2)(n^{-(2+\delta)}) = n^{-\delta}.$$

Next, consider the remaining larger cuts. According to Theorem 2.6, there are less than $n^{2\alpha}$ cuts of value at most αc. Since we have numbered the cuts in increasing order, this means that $c_{n^{2\alpha}} > \alpha c$. In other words, writing $k = n^{2\alpha}$,

$$c_k > \frac{\ln k}{2 \ln n} \cdot c$$

and thus

$$\begin{aligned} p_k &< (p^c)^{\frac{\ln k}{2\ln n}} \\ &= (n^{-(2+\delta)})^{\frac{\ln k}{2\ln n}} \\ &= k^{-(1+\delta/2)}. \end{aligned}$$

It follows that

$$\begin{aligned} \sum_{k>n^2} p_k &< \sum_{k>n^2} k^{-(1+\delta/2)} \\ &\leq \int_{n^2}^{\infty} k^{-(1+\delta/2)}\, dk \\ &\leq 2n^{-\delta}/\delta. \end{aligned}$$

Summing the bounds for the first n^2 and for the remaining cuts gives a total of $n^{-\delta} + 2n^{-\delta}/\delta$, as claimed.

The proof of Part 2 is the same, except that we sum only over those cuts of value at least αc. □

Remark. A slightly stronger version of Part 1 was first proved by Lomonosov and Polesskii [22] using different techniques that identified the cycle as the most unreliable graph for a given c and n. We sketch their result, which we need for a different purpose, in Section 4.3.2. However, Part 2 is necessary for the FPRAS and was not previously known.

2.4 An Approximation Algorithm

Our proof that only small cuts matter leads immediately to an FPRAS. First we outline our solution. Given that $\mathrm{FAIL}(p) < n^{-4}$, Theorem 2.9 shows that the probability that a cut of value much larger than c fails is negligible, so we need only determine the probability that a cut of value near c fails. We do this as follows. First, we enumerate the (polynomial size) set of near-minimum cuts that matter. From this set we generate a polynomial size boolean expression (with a variable for each edge, true if the edge has failed) that is true if any of our near-minimum cuts has failed. We then need to determine the probability that this boolean expression is true; this can be done using the DNF counting techniques of Karp, Luby, and Madras [18, 17]. Details are given in the following theorem.

Theorem 2.10. *When* $\mathrm{FAIL}(p) < n^{-4}$*, there is a (Monte Carlo) FPRAS for estimating* $\mathrm{FAIL}(p)$ *running in* $\tilde{O}(mn^4/\epsilon^3)$ *time.*

Proof. Under the assumption, the probability that a particular minimum cut fails is $p^c \leq \mathrm{FAIL}(p) \leq n^{-4}$. We show there is a constant α for which the probability that any cut of value greater than αc fails is at most $\epsilon\mathrm{FAIL}(p)$. This proves that to approximate to the desired accuracy we need only determine the probability that some cut of value less than αc fails. It remains to determine α.

Write $p^c = n^{-(2+\delta)}$; by hypothesis $\delta \geq 2$. Thus by Theorem 2.9, the probability that a cut larger than αc fails is at most $2n^{-\delta\alpha}$. On the other hand, we know that $n^{-(2+\delta)} = p^c \leq \text{FAIL}(p)$, so it suffices to find an α for which $2n^{-\delta\alpha} \leq \epsilon n^{-(2+\delta)}$. Solving this shows that $\alpha = 1+2/\delta-(\ln(\epsilon/2))/\delta \ln n \leq 2-\ln(\epsilon/2)/2\ln n$ suffices and that we therefore need only examine the smallest $n^{2\alpha} = O(n^4/\epsilon)$ cuts.

We can enumerate these cuts in $O(n^{2\alpha}\log^3 n)$ time using certain randomized algorithms [14, 11] (a somewhat slower deterministic algorithm exists [26]). Suppose we assign a boolean variable x_e to each edge e; x_e is true if edge e fails and false otherwise. Therefore, the x_e are independent and true with probability p. Let E_i be the set of edges in the i^{th} small cut. Since the i^{th} cut fails if and only if all edges in it fail, the event of the i^{th} small cut failing can be written as $F_i = \wedge_{e\in E_i} x_e$. Then the event of at least one small cut failing can be written as $F = \vee_i F_i$. We wish to know the probability that F is true. Note that F is a formula in disjunctive normal form. The size of the formula is equal to the number of clauses ($n^{2\alpha}$) times the number of variables per clause (at most αc), namely $O(cn^{2\alpha})$. The FPRAS of Karp, Luby, and Madras [17] estimates the truth probability of this formula, and thus the failure probability of the small cuts, to within $(1 \pm \epsilon)$ in $\tilde{O}(cn^{2\alpha}/\epsilon^2) = \tilde{O}(cn^4/\epsilon^3) = \tilde{O}(mn^4/\epsilon^3)$ time.

We are therefore able to estimate to within $(1\pm\epsilon)$ the value of a probability (the probability that some α-minimum cut fails) that is within $(1 \pm \epsilon)$ of the probability of the event we really care about (the probability that some cut fails). This gives us an overall estimate accurate to within $(1 \pm \epsilon)^2 \approx (1 \pm 2\epsilon)$. □

2.5 Putting it Together

We now combine the above results to get an FPRAS:

Corollary 2.11. *There is an FPRAS for* FAIL(p) *running in* $\tilde{O}(mn^4/\epsilon^3)$ *time.*

Proof. Suppose we wish to estimate the failure probability to within a $(1 \pm \epsilon)$ ratio. If $\text{FAIL}(p) > n^{-4}$, then we can estimate it in $\tilde{O}(mn^4/\epsilon^2)$ time by direct Monte Carlo simulation as in Corollary 2.4. Otherwise, we can run the $\tilde{O}(mn^4/\epsilon^3)$-time algorithm of Theorem 2.10. □

If the graph is sparse (with $O(n)$ edges) and the minimum cut is $\tilde{O}(1)$ (both these conditions apply to, e.g., planar graphs) then the time for a Monte Carlo trial is $O(n)$, while the size of the formula for the DNF counting step above is $\tilde{O}(n^{2\alpha})$. So if we use a different FAIL(p) threshold for deciding which algorithm to use, we can improve the running time bound to $\tilde{O}(n^{3.8}/\epsilon^2)$.

While this time bound is still rather poor, experiments have suggested that performance in practice is significantly better—typically $\tilde{O}(n^3)$ on sparse graphs [16].

3 Extensions

We now discuss several extensions of our basic FPRAS. In this section, we will consider many cases in which it is sufficient to consider the probability that an

α-minimum cut fails for some $\alpha = O(1 - \log \epsilon / \log n)$ (as in the previous section) that is understood in context but not worth deriving explicitly. We will refer to these α-minimum cuts as the *weak* cuts of the graph.

3.1 Varying Failure Probabilities

The analysis and algorithm given above extend to the case where each edge e has its own failure probability p_e. To extend the analysis, we transform a graph with varying edge failure probabilities into one with identical failure probabilities. Given the graph G with specified edge failure probabilities, we build a new graph H all of whose edges have the same failure probability p, but that has the same failure probability as G. Choose a small parameter θ. Replace an edge e of failure probability p_e by a "bundle" of k_e parallel edges, each with the same endpoints as e but with failure probability $1-\theta$, where

$$k_e = \lceil -(\ln p_e)/\theta \rceil .$$

This bundle of edges keeps its endpoints connected unless all the edges in the bundle fail; this happens with probability

$$(1-\theta)^{\lceil -(\ln p_e)/\theta \rceil}.$$

As $\theta \to 0$, this failure probability converges to p_e. Therefore, the reliability of H converges as $\theta \to 0$ to the reliability of G. Thus, to determine the failure probability of G, it suffices to determine the failure probability of H in the limit as $\theta \to 0$.

Since H has all edge failure probabilities the same, our Section 2 analysis of network reliability applies to H. In particular, we know that it suffices to enumerate the weak cuts of H and then determine the probability that one of them fails. To implement this idea, note that changing the parameter θ scales the values of cuts in H without changing their relative values (modulo a negligible rounding error). We therefore build a weighted graph F by taking graph G and giving weight $\ln 1/p_e$ to edge e. The weak cuts in F correspond to the weak cuts in H. We find these weak cuts in F using the Contraction Algorithm (which works for weighted graphs [15]) as before.

Given the weak cuts in H, we need to determine the limiting probability that one of them fails as $\theta \to 0$. We have already argued that as $\theta \to 0$, the probability a cut in H fails converges to the probability that the corresponding cut in G fails. Thus we actually want to determine the probability that one of a given set of cuts in G fails. We do this as before: we build a boolean formula with variables for the edges of G and with a clause for each weak cut that is true if all the edges of the cut fail. The only change is that variable x_e is set to true with probability p_e. The algorithm of [17] works with these varying truth probabilities and computes the desired quantity.

Theorem 3.1. *There is an FPRAS for the all-terminal network reliability problem with varying edge failure probabilities.*

One might be concerned by the use of logarithms to compute edge weights. However, it is easy to see that in fact approximate logarithms suffice for the purpose of enumerating small cuts. If we approximate each logarithm to within relative error .1, then every α-minimum cut in F remains an $11\alpha/9$-minimum cut in the approximation to F. Thus we can enumerate a slightly larger set of near-minimum cuts in order to find the weak cuts. Once we find the weak cuts, we use the original p_e values in the DNF counting algorithm.

In the case of varying failure probabilities, we cannot bound the number of edges in any particular weak cut by a quantity less than m (a weak cut may have $m-n$ edges with large failure probabilities). Thus the size of the DNF formula, and thus the running time of the DNF counting algorithm, may be as large as $mn^{2\alpha} \approx mn^4/\epsilon$.

All the other extensions described in this paper can also be modified to handle varying failure probabilities. But for simplicity, we focus on the uniform case.

3.2 Multiterminal Reliability

The multiterminal reliability problem is a generalization of the all-terminal reliability problem. Instead of asking whether the graph becomes disconnected, we consider a subset K of the vertices and ask if some pair of them becomes disconnected. If some pair of vertices in K is separated by a cut of value $O(c)$, then we can use the same theorem on the exponential decay of cut failure probabilities to prove that we only need to examine the small cuts in the graph to determine whether some pair of vertices in K becomes disconnected.

Lemma 3.2. *If some pair of vertices in K is separated by a cut of value $O(c)$, then there is an FPRAS for the multiterminal reliability problem with source vertices K.*

Proof. We focus on the case of uniform failure probability p; the generalization to arbitrary failure probabilities is as before. Suppose a cut of value βc separates vertices in K. Then the probability that K gets disconnected when edges fail with probability p is at least $p^{\beta c}$. If $p^c > n^{-4}$, then $p^{\beta c} > n^{-4\beta} = n^{-O(1)}$ and we use Monte Carlo simulation as before to estimate the failure probability. If $p^c < n^{-4}$, then by Theorem 2.9, the probability that a cut of value exceeding αc fails is $O(n^{-2\alpha})$. Thus, choosing α such that $n^{-2\alpha} \le \epsilon p^{\beta c}$, we can enumerate the weak cuts and apply DNF counting. □

3.3 k-Connectivity

Just as we estimated the probability that the graph fails to be connected, we can estimate the probability that it fails to be k-edge connected for any constant k. Note that the graph fails to be k-edge connected only if some cut has less than k of its edges survive. The probability of this event decays exponentially with the value of the cut, allowing us to prove (as with Theorem 2.9) that if the probability that fewer than k edges in a minimum cut survive is $O(n^{-(2+\delta)})$, then the probability that fewer than k edges survive in a non-weak cut is negligible. Thus, if direct Monte Carlo simulation is not applicable, we need only determine the probability that some weak cut keeps less than k of its edges. But this is another DNF counting problem. For any particular weak cut containing $C \leq m$ edges, we enumerate all $\binom{C}{C-k+1} = O(C^{k-1}) = O(m^{k-1})$ sets of $C-k+1$ edges, and for each add a DNF clause that is true if all the given edges fail.

In fact, one can also adapt the algorithm of [17] to determine the probability that all but $k-1$ variables in some clause of a DNF formula become true; thus we can continue to work with the $O(mn^4/\epsilon)$-size formula we used before.

Corollary 3.3. *For any constant k, there is an FPRAS for the probability that a graph with edge failure probabilities fails to be k-edge connected.*

3.4 Eulerian Directed Graphs

A natural generalization of the all-terminal reliability problem to directed graphs is to ask for the probability that a directed graph with random edge failures remains strongly connected. A directed graph fails to be strongly connected precisely when all the edges in some *directed* cut fail. In general, the techniques of this paper cannot be applied to directed graphs—the main reason being that a directed graph can have exponentially many minimum directed cuts.

We can, however, handle one special case. In an *Eulerian* directed graph G on vertex set V, the number of edges crossing from any vertex set A to $V-A$ is equal to the number of edges crossing from $V-A$ to A. Thus if we construct an undirected graph H by removing the directions from the edges of G, we know that any (directed) cut in G has value equal to half that of the corresponding (undirected) cut in H. It follows that the α-minimum directed cuts of G correspond to α-minimum undirected cuts of H. Therefore, there are at most $2n^{2\alpha}$ α-minimum directed cuts in G that can be enumerated by enumerating the α-minimum cuts of H (the factor of 2 arises from considering both directions for each cut). As in the undirected case, if the directed failure probability is less than n^{-4}, an analogue of Theorem 2.9 immediately follows, showing that only weak directed cuts are likely to fail. It therefore suffices to enumerate a polynomial number of weak directed cuts to estimate the directed failure probability.

Corollary 3.4. *There is an FPRAS for the probability that a directed Eulerian graph fails to remain strongly connected under random edge failures.*

Corollary 3.5. *For any constant k there is an FPRAS for the probability that a directed Eulerian graph fails to have directed connectivity k under random edge failures.*

3.5 Random Orientations

In a similar fashion, we can estimate the probability that, if we orient each edge of the graph randomly, the graph fails to be strongly connected. For each cut, we make a DNF formula with two clauses, one of which is true if all edges point "left" and the other if all edges point "right." (This observation is due to Alan Frieze.) This problem can also be phrased as estimating the number of non-strongly connected orientations of an undirected graph; in this form, it is related to the *Tutte polynomial* discussed in Section 6. Similarly, we can estimate the probability that random orientations fail to produce a k-connected directed graph.

4 Partition into r Components

The quantity FAIL(p) is an estimate of the probability that the graph partitions into more than one connected component. We can similarly estimate the probability that the graph partitions into r or more components for any constant r. Besides its intrinsic interest, the analysis of this problem will be important in our study of some heuristics and derandomizations in Section 5 and the Tutte polynomial in Section 6.

We first note that a graph partitions into r or more components only if an *r-way cut*—the set of edges with endpoints in different components of an r-way vertex partition—loses all its edges. Note that some of the vertex sets of the partition might induce disconnected subgraphs, so that the r-way partition might induce more than r connected components. However, it certainly does not induce less. Our approach to r-way reliability is the same as for the 2-way case: we show that there are few small r-way cuts and that estimating the probability one fails suffices to approximate the r-way failure probability. As a corollary, we show that the probability of r-way partition is much less than that of 2-way partition.

4.1 Counting Multiway Cuts

We enumerate multiway cuts using the Contraction Algorithm as for the 2-way case. Details can be found in [15].

Lemma 4.1. *In an m-edge unweighted graph the minimum r-way cut has value at most $2m(r-1)/n$.*

Proof. A graph's average degree is $2m/n$. Consider an r-way cut with each of the $r-1$ vertices of smallest degree as its own singleton component and all the remaining vertices as the last component. The value of this cut is at most the sum of the singleton vertex degrees, which is at most $r-1$ times the average degree. □

Corollary 4.2. *There are at most $\binom{n}{2(r-1)}$ minimum r-way cuts.*

Proof. Suppose we fix a particular r-way minimum cut and run the Contraction Algorithm until we have $2(r-1)$ vertices. By the previous lemma, the probability that we pick an edge of our fixed cut when k vertices remain is at most $2\frac{r-1}{k}$. Thus the probability that our fixed minimum r-way cut is chosen is

$$\prod_{k=2r-1}^{n}\left(1-\frac{2(r-1)}{k}\right)$$

which is analyzed exactly as in the proof of Theorem 2.6, substituting $r-1$ for α. □

Corollary 4.3. *For arbitrary $\alpha \geq 1$, there are at most $(rn)^{2\alpha(r-1)}$ α-minimum r-way cuts that can be enumerated in $\tilde{O}((rn)^{2\alpha(r-1)})$ time.*

Proof. First run the Contraction Algorithm until the number of vertices remaining is $\lceil 2\alpha(r-1)\rceil$. At this point, choose a random r-way partition of what remains. There are at most $r^{2\alpha(r-1)}$ such partitions.

The time bound follows from the analysis of the Recursive Contraction Algorithm [15]. □

Remark. We conjecture that in fact the correct bound is $O(n^{\alpha r})$ α-minimum r-way cuts. Section 4.3.2 shows this is true for $\alpha = 1$. Proving it for general α would slightly improve our exponents in the following sections.

4.2 An Approximation Algorithm

Our enumeration of multiway cuts allows an analysis and reduction to DNF counting exactly analogous to the one performed for FAIL(p).

Corollary 4.4. *Suppose a graph has r-way minimum cut value c_r and that each edge fails with probability p, where $p^{c_r} = (rn)^{-(2+\delta)(r-1)}$ for some constant $\delta > 0$. Then the probability that an α-minimum r-way cut fails is at most $(rn)^{-\alpha\delta(r-1)}(1+2/\delta)$*

Proof. The proof is exactly as for Theorem 2.9, substituting $(rn)^{(r-1)}$ (drawn from Corollary 4.3) for n everywhere. □

Corollary 4.5. *There is an algorithm for ϵ-approximating the probability that a graph partitions into r or more components, running in $\tilde{O}(m(rn)^{4(r-1)}/\epsilon^3)$ time. The algorithm is an FPRAS with running time $\tilde{O}(mn^{4(r-1)}/\epsilon^3)$ for any fixed r.*

Proof. Exactly as for the 2-way cut case, with $(rn)^{(r-1)}$ replacing n everywhere. Let c_r be the r-way minimum cut value and let δ be defined by $p^{c_r} = (rn)^{-(2+\delta)(r-1)}$. If $p^{c_r} > (rn)^{-4(r-1)}$, estimate the partition probability via Monte Carlo simulation. Otherwise, it follows as in the 2-way cut case that for the same constant α as we chose there, the probability that a greater than α-minimum r-way cut fails is less than ϵp^{c_r}. Thus to estimate the partition probability it suffices to enumerate (in $\tilde{O}((rn)^{4(r-1)}/\epsilon)$ time) the set of α-minimum r-way cuts and perform DNF counting. □

One might wish to compute the probability that a graph partitions into *exactly* r components, but it is not clear that this can be done. In particular, computing REL(p) can be reduced to this problem (for any r) by adding $r-1$ isolated vertices. There is at present no known FPRAS for REL(p).

4.3 Comparison to 2-way Cuts

For Sections 5 and 6, we need to show that the probability of partition into r components is much less than that of partition into 2 components. We give two proofs, the first simpler but with a slightly weaker bound. The following sections can use the weaker analysis at the cost of worse exponents. In this section, the term "cut" refers exclusively to 2-way cuts unless we explicitly modify it.

4.3.1 A simple argument

Lemma 4.6. *If $p^c = n^{-(2+\delta)}$, then the probability that an r-way cut fails is at most $n^{-\delta r/4}(1+2/\delta)$.*

Proof. We show that any r-way cut contains the edges of a (2-way) cut of value $rc/4$. Thus, if an r-way cut fails then an $(r/4)$-minimum 2-way cut fails. The probability that this happens has been upper-bounded by Theorem 2.9.

To show the claim, consider an r-way cut. Contract each component of the r-way partition to a single vertex, yielding an r-vertex graph G'. All edges in this graph correspond to edges of the r-way cut. Every cut in G' corresponds to a cut of the same value in the original graph, so it suffices to show that G' has a 2-way cut of value at least $rc/4$. To see this, note that every vertex in G' has degree at least c, so the number of edges in G' is at least $rc/2$. Consider a random cut of G', generated by assigning each vertex randomly to one side or the other. Each edge has a $1/2$ chance of being cut by this partition, so the expected value of this cut is at least $rc/4$. It follows that G' has a cut of value at least $rc/4$ that corresponds to a cut of value at least $rc/4$ in the original graph. □

4.3.2 A better argument

We can get a slightly better bound on the probability that a graph partitions into r components via a small variation on an argument made by Lomonosov and Polesskii [22, 20, 4]. The better bound improves some of our exponents. Their proof uses techniques somewhat different from the remainder of the paper and can safely be skipped.

Lemma 4.7. *Let $\mathrm{FAIL}_r(G,p)$ denote the probability that G partitions into r or more connected components when each edge fails with probability p. Let G have minimum cut c for some even c. Let C_n be a cycle with $c/2$ edges between adjacent vertices. Then for any r, $\mathrm{FAIL}_r(G,p) \leq \mathrm{FAIL}_r(C_n,p)$.*

Corollary 4.8. *For any graph G with minimum cut c, if edges fail with probability p where $p^c = n^{-(2+\delta)}$, then the probability the failed graph has r or more connected components is less than $n^{-\delta r/2}$.*

Remark. Note that for $r = 2$, the above result gives a slightly stronger bound on FAIL(p) than we are able to get in Theorem 2.9. Unfortunately, this argument does not appear to extend to proving the bound we need on the probability that a greater than α-minimum r-way cut fails.

Proof of Corollary 4.8: Thanks to Lemma 4.7, it suffices to prove this claim for the case of G a cycle C_n with $(c/2)$-edge "bundles" between adjacent vertices. The number of components into which C_n is partitioned is equal to the number of bundles that fail, so we need only bound the probability that r or more bundles fail. The probability that a single bundle fails is $p^{c/2} = n^{-(1+\delta/2)}$, so the probability that r particular bundles fail is $n^{-r(1+\delta/2)}$. There are $\binom{n}{r} < n^r$ sets of exactly r bundles. It follows that the probability r or more bundles fail is less than $n^r n^{-r(1+\delta/2)} = n^{-r\delta/2}$. □

Proof of Lemma 4.7: Consider the following time-evolving version of the Contraction Algorithm on a connected graph G. Each edge of G is given an *arrival time* chosen independently from the exponential distribution with mean 1. Each time an edge arrives, we contract its endpoints if they have not already been contracted. This gives rise to a sequence of graphs $G = G_n, G_{n-1}, \ldots, G_1$, where G_r has r vertices. Let $G[t]$ be the graph that exists at time t. Thus initially $G[0] = G_n$ and eventually $G[\infty]$ has one vertex since all edges have arrived. We draw a correspondence between this model and our edge failure model as follows: at time t, the failed edges are those which have not yet arrived. It follows that each vertex in $G[t]$ corresponds to a connected component of G when each edge has failed (to arrive) independently with probability e^{-t}.

We consider the random variable $T_r(G)$ defined as the time at which the edge that contracts G_r to G_{r-1} arrives. We show that $T_r(C_n)$ *stochastically dominates* $T_r(G)$ for every r—that is,

$$\Pr[T_r(G) \geq t] \leq \Pr[T_r(C_n) \geq t].$$

(See Motwani and Raghavan [23] for additional discussion of this definition.) Assuming this is true, we can prove our result as follows:

$$\begin{aligned}
\Pr[G[t] \text{ has } r \text{ or fewer components}] &= \Pr[T_r(G) \leq t] \\
&\geq \Pr[T_r(C_n) \leq t] \\
&= \Pr[C_n[t] \text{ has } r \text{ or fewer components}].
\end{aligned}$$

To prove stochastic domination, let $t_r(G) = T_{r-1}(G) - T_r(G)$ denote the length of time for which G_r exists before being contracted to G_{r-1}. Clearly, $t_r(G)$ is just the time it takes for an edge to arrive that has endpoints in different connected components of G_r. It follows that $T_r(G) = \sum_{r'=r}^{n} t_{r'}(G)$. Similarly, $T_r(C_n) = \sum_{r'=r}^{n} t_{r'}(C_n)$. We will show that $t_r(C_n)$ stochastically dominates $t_r(G)$ for every r. Thanks to the memoryless nature of the exponential distribution, the t_r are mutually independent (this will be justified more carefully later). The fact that $T_r(C_n)$ stochastically dominates $T_r(G)$ then follows from the fact that when X dominates X' and Y dominates Y' and the variables are independent, $X+Y$ dominates $X'+Y'$.

To analyze t_r, suppose there are m_r edges in G_r (note m_r is a random variable). The arrival time of each edge in G_r measured from $T_r(G)$ is exponentially distributed with mean 1. Therefore, the arrival time of the first such edge, namely $t_r(G)$, is exponentially distributed with mean $1/m_r$. Now note that G_r is c-connected, so it must have $m_r \geq cr/2$. It follows that $t_r(G)$ is exponentially distributed with mean at most $2/cr$, meaning that it is stochastically dominated by any exponentially distributed variable with mean $2/cr$. On the other hand, when C_n has been reduced to r components, it is isomorphic to C_r. By the same analysis as for G, we know $t_r(C_n)$ is exponentially distributed with mean $2/cr$, and thus stochastically dominates $t_r(G)$.

Our glib claim that the t_r are independent needs some additional justification. Technically, we condition on the values $G_n, \ldots, G_1$ of the evolving graph. We show that regardless of what values G_i we condition on, $T_r(C_n)$ stochastically dominates $T_r(G \mid G_n, \ldots, G_1)$. Since the stochastic domination applies regardless of our conditioning event, it follows even if we do not condition.

Once we have conditioned on the value G_r, t_r is just the time it takes for an edge to arrive that contracts G_r to G_{r-1} and is therefore independent of $t_{r'}$ when $r' \neq r$. But we must ask whether t_r still has the right exponential distribution—the complicating factor being that we know the first edge to arrive at G_r must contract G_r to a specific G_{r-1} and not some other graph. To see that this does not matter, let B be the event that first edge to arrive at G_r is one that creates G_{r-1}. Then

$$\begin{aligned}
\Pr[t_r \geq t \mid B] &= \Pr[B \mid t_r \geq t] \Pr[t_r \geq t] / \Pr[B] \\
&= \Pr[B] \Pr[t_r \geq t] / Pr[B] \\
&= \Pr[t_r \geq t]
\end{aligned}$$

since of course, the time of arrival of the edge the contracts G_r has no impact on which of the edges of G_r is the first to arrive. □

5 Heuristics and Deterministic Algorithms

Until now, we have relied on the fact that the most likely way for a graph to fail is for some of its near-minimum cuts to fail. We now strengthen this argument to observe that most likely, *exactly one* of these near-minimum cuts fails. This leads to two additional results. First, we show that the sum of the individual small-cut failure probabilities is a reasonable approximation to the overall failure probability. This justifies a natural heuristic and indicates that in practice one might not want to bother with the DNF counting phase of our algorithm. In a more theoretical vein, we also give a deterministic PAS for FAIL(p) that applies whenever FAIL$(p) < n^{-(2+\delta)}$. We prove the following theorems.

Theorem 5.1. *When $p^c < n^{-4}$ (and in particular when* $\mathrm{FAIL}(p) < n^{-4}$*), the sum of the weak cuts' failure probabilities is a* $(1 + o(1))$ *approximation to* $\mathrm{FAIL}(p)$.

Theorem 5.2. *When $p^c < n^{-(2+\delta)}$ for any constant δ (and in particular when* $\mathrm{FAIL}(p) < n^{-(2+\delta)}$*), there is a deterministic PAS for* $\mathrm{FAIL}(p)$ *running in*

$$(n/\epsilon)^{\exp(O(-\log_n \epsilon))}$$

time.

We remark that unlike many PASs whose running times are only polynomial for constant ϵ, our PAS has polynomial running time so long as $\epsilon = n^{-O(1)}$. But its behavior when ϵ is tiny prevents it from being an FPAS.

To prove these theorems, we argue as follows. As shown in Section 2, it is sufficient to approximate, for the given ϵ, the probability that some α-minimum cut fails, where

$$\alpha = 1 + 2/\delta - (\ln \epsilon)/\delta \ln n$$

Let us write these α-minimum cuts as C_i, $i = 1, \ldots, n^{2\alpha}$. Let F_i denote the event that cut C_i fails. We can use inclusion-exclusion to write the failure probability as

$$\Pr[\cup F_i] = \sum_{i_1} \Pr[F_{i_1}] - \sum_{i_1 < i_2} \Pr[F_{i_1} \cap F_{i_2}] + \sum_{i_1 < i_2 < i_3} \Pr[F_{i_1} \cap F_{i_2} \cap F_{i_3}] + \cdots.$$

Later terms in this summation measure events involving many cut failures. We show that when many cuts fail, the graph partitions into many pieces, meaning a multiway cut fails. We then argue (using Lemma 4.6 or Corollary 4.8) that this is so unlikely that later terms in the sum can be ignored. This immediately yields Theorem 5.1.

To prove Theorem 5.2, we show that for any fixed ϵ it is sufficient to consider a constant number of terms (summations) on the right-hand side in order to get a good approximation. Observe that the k^{th} term in the summation can be computed deterministically in $O(m(n^{2\alpha})^k)$ time by evaluating the probability of each of the $(n^{2k\alpha})$ intersection events in the sum (each can be evaluated deterministically since it is just the probability that all edges in the specified cuts fail). Thus, our running time will be polynomial so long as the number of terms we need to evaluate is constant.

5.1 Inclusion-Exclusion Analysis

As discussed above, our analyses use a truncation of the inclusion-exclusion expression for

$$\Pr[\cup F_i] = \sum_{i_1} \Pr[F_{i_1}] - \sum_{i_1 < i_2} \Pr[F_{i_1} \cap F_{i_2}] + \sum_{i_1 < i_2 < i_3} \Pr[F_{i_1} \cap F_{i_2} \cap F_{i_3}] + \cdots.$$

Suppose we truncate the inclusion-exclusion, leaving out the k^{th} and later terms. If k is odd the truncated sum yields a lower bound; if k is even it yields an upper bound. We show that this bound is sufficiently tight. We do so by rewriting the inclusion-exclusion expression involving particular sets of failed cuts failing as an expression based on *how many* cuts fail.

Lemma 5.3. *Let S_u be the event that u* or more *of the events F_i occur. If the inclusion-exclusion expansion is truncated at the k^{th} term, the error introduced is*

$$\sum_u \binom{u-2}{k-2} \Pr[S_u].$$

Proof. Let T_u be the event that *exactly* u of the events F_i occur. Consider the first summation $\sum F_{i_1}$ in the inclusion-exclusion expansion. The event that precisely the events $F_{j_1}, \ldots, F_{j_u}$ occur (that is, the event that cuts $C_{j_1}, \ldots, C_{j_k}$ fail but no others fail) contributes to the u terms $\Pr[F_{j_1}], \ldots, \Pr[F_{j_u}]$ in the sum. It follows that each sample point contributing to T_u is counted $u = \binom{u}{1}$ times in the summation. Thus,

$$\sum \Pr[F_{i_1}] = \sum_u \binom{u}{1} \Pr[T_u].$$

By the same reasoning,

$$\sum \Pr[F_{i_1} \cap F_{i_2}] = \sum_u \binom{u}{2} \Pr[T_u],$$

and so on. It follows that the error introduced by truncation at term k is

$$\begin{aligned}
\sum_{i_1 < i_2 < \cdots < i_k} \Pr[F_{i_1} \cap F_{i_2} \cdots \cap F_{i_k}] - \sum_{i_1 < i_2 < \cdots < i_{k+1}} \Pr[F_{i_1} \cap F_{i_2} \cap \cdots F_{i_{k+1}}] + \cdots \\
= \sum_{j \geq k} (-1)^{k-j} \sum_u \binom{u}{j} \Pr[T_u] \\
= \sum_u \sum_{j \geq k} (-1)^{k-j} \binom{u}{j} \Pr[T_u] \\
= \sum_u \binom{u-1}{k-1} \Pr[T_u].
\end{aligned}$$

Now recall that S_u is the event that u *or more* of the F_i occur, meaning that

$\Pr[T_u] = \Pr[S_u] - \Pr[S_{u+1}]$. Thus we can rewrite our bound above as

$$\begin{aligned}
&\sum_u \binom{u-1}{k-1}(\Pr[S_u] - \Pr[S_{u+1}]) \\
&\quad = \sum_u \binom{u-1}{k-1}\Pr[S_u] - \sum_u \binom{u-1}{k-1}\Pr[S_{u+1}] \\
&\quad = \sum_u \binom{u-1}{k-1}\Pr[S_u] - \sum_u \binom{u-2}{k-1}\Pr[S_u] \\
&\quad = \sum_u \left(\binom{u-1}{k-1} - \binom{u-2}{k-1}\right)\Pr[S_u] \\
&\quad = \sum_u \binom{u-2}{k-2}\Pr[S_u].
\end{aligned}$$

This completes the proof. □

5.2 A Simple Approximation

Using the above error bound, we can prove Theorem 5.1. Let F_i denote the event that the i^{th} near-minimum cut fails. Our objective is to estimate $\Pr[\cup F_i]$. Summing the individual cuts' failure probabilities corresponds to truncating our inclusion-exclusion sum at the second term, giving (by Lemma 5.3) an error of $\sum_{u\geq 2} S_u$. We now bound this error by bounding the quantities S_u.

Lemma 5.4. *If u distinct (2-way) cuts fail then a $\lceil\log(u+1)+1\rceil$-way cut fails.*

Proof. Consider a configuration in which u distinct cuts have failed simultaneously. Suppose this induces k connected components. Let us contract each connected component in the configuration to a single vertex. Each failed cut in the original graph corresponds to a distinct failed cut in the contracted graph. Since the contracted graph has k vertices, we know that there are at most $2^{k-1}-1$ ways to partition its vertices into two nonempty groups, and thus at most this many cuts. In other words, $u \leq 2^{k-1}-1$. Now solve for u and observe it must be integral. □

Corollary 5.5. *If $p^c = n^{-(2+\delta)}$ then $\Pr[S_u] \leq n^{-\lceil\log(u+1)+1\rceil\delta/2}$.*

Proof. Apply Corollary 4.8 to the previous lemma. □

Thus, for example, S_2 and S_3 are upper bounded by the probability that a 3-way cut fails, which by Corollary 4.8 is at most $n^{-3\delta/2}$. More generally, all 2^k values $S_{2^k}, \ldots, S_{2^{k+1}-1}$ are at most $n^{-(k+2)\delta/2}$. It follows that the error in our approximation by the bound of Theorem 5.1 is

$$\begin{aligned}
\sum_{u\geq 2} S_u &\leq \sum_{k\geq 1} 2^k n^{-(k+2)\delta/2} \\
&= n^{-\delta}\sum_{k\geq 1}(2n^{-\delta/2})^k \\
&= 2n^{-3\delta/2}(1+o(1))
\end{aligned}$$

whenever $\delta > 0$. This quantity is $o(p^c)$, and thus $o(\mathrm{FAIL}(p))$, whenever $n^{-3\delta/2} = o(n^{-(2+\delta)})$, i.e. $\delta > 4$. This proves Theorem 5.1.

5.3 A PAS

We now use the inclusion-exclusion analysis to give a PAS for FAIL(p) when $p^c = n^{-(2+\delta)}$ for some fixed $\delta > 0$, thus proving Theorem 5.2. We give an ϵ-approximation algorithm with a running time of $(n/\epsilon)^{\exp(O(-\log_n \epsilon))}$, which is clearly polynomial in n for each fixed ϵ (and in fact, for any $\epsilon = n^{-O(1)}$).

We must eliminate two uses of randomization: in the Contraction Algorithm for identifying the α-minimum cuts and in the DNF counting algorithm for estimating their failure probability.

The first step is to deterministically identify the near-minimum cuts of G. One approach is to use a derandomization of the Contraction Algorithm [13]. A more efficient approach is to use a cut enumeration scheme of Vazirani and Yannakakis [26]. This scheme enumerates cuts in increasing order of value, with a "delay" of $\tilde{O}(mn)$ per cut. From the fact that there are only $n^{2\alpha}$ weak cuts, it follows that all weak cuts (in the sense of Section 3) can be found in $\tilde{O}(mn^{1+2\alpha})$ time.

We must now estimate the probability one of the near-minimum cuts fails. Let us consider truncating to the first k terms in the inclusion-exclusion expansion. From Corollary 5.5 we know that $\Pr[S_u] \leq n^{-(\log(u+1)+1)\delta/2}$. It follows from Lemma 5.3 that for any $k \leq \frac{1}{3}\delta \log n$, our error from using the k-term truncation of inclusion-exclusion is

$$\begin{aligned}
\sum_u \binom{u-2}{k-2} n^{-(\log(u+1)+1)\delta/2} &\le n^{-\delta/2}\sum_{u\ge k}(u-2)^{k-2}(u+1)^{-\delta(\log n)/2} \\
&\le \sum_{u\ge k}(u+1)^{k-2-\delta(\log n)/2} \\
&\le \sum_{u\ge k}(u+1)^{\delta(\log n)/3-2-\delta(\log n)/2} \\
&\le \sum_{u\ge k}(u+1)^{-\delta(\log n)/6-1} \\
&\le \int_{u=k-1}^{\infty}(u+1)^{-\delta(\log n)/6-1}\, \boldsymbol{du} \\
&= \frac{k^{-\delta(\log n)/6}}{\delta(\log n)/6} \\
&= \frac{n^{-\delta(\log k)/6}}{\delta(\log n)/6} \\
&= O(n^{-\delta(\log k)/6})
\end{aligned}$$

This quantity is $O(\epsilon n^{-(2+\delta)}) = O(\epsilon p^c) = O(\epsilon \mathrm{FAIL}(p))$ for some $k = 2^{O(-\log_n \epsilon)}$. It follows that for an ϵ-approximation we need only evaluate the inclusion-exclusion up to the k^{th} term. Computing the k^{th} term requires examining every set of k of the $(n/\epsilon)^{O(1)}$ α-minimum cuts; this requires $(n/\epsilon)^{\exp(O(-\log_n \epsilon))}$ time. This concludes the proof of Theorem 5.2.

We can slightly improve our bound on $\Pr[S_u]$, which in turn gives better bounds on k.

Lemma 5.6. *If u distinct α-minimum cuts fail, then a $u^{1/2\alpha}$-way cut fails.*

Proof. Consider a configuration in which u distinct cuts have failed simultaneously. Suppose this induces k connected components. Let us contract each connected component in the configuration to a single vertex. In this contracted graph (before edges fail), the minimum cut is at least c (since contraction never reduces the minimum cut). Furthermore, each of the u failed cuts is a cut of value at most αc, and thus an α-minimum cut, in the contracted graph. Since the contracted graph has k vertices, we know from Theorem 2.6 that $u < k^{2\alpha}$, meaning that $k > u^{1/2\alpha}$. □

However, this serves only to reduce the values of our constants (and reduce the running time from an exponential to a polynomial dependence on $1/\delta$).

6 The Tutte Polynomial

The *Tutte Polynomial* $T(G; x, y)$ is a polynomial in two variables defined by a graph G. Evaluating it at various points (x, y) on the so-called *Tutte Plane* yields various interesting quantities regarding the graph. In particular, computing the network reliability REL(p) is the special case of evaluating the Tutte polynomial at the point $x = 1, y = 1/p$. Another special case is counting the number of strongly connected orientations of an undirected graph, discussed in Section 3.5. Yet another is counting the number of forests in a graph. Alon, Frieze, and Welsh [1] showed that for any *dense* graph (one with $\Omega(n^2)$ edges) and fixed x and fixed $y \geq 1$ there is an FPRAS for the Tutte polynomial.

6.1 Results

In this section, we prove the following.

Theorem 6.1. *For every $y > 1$ there is a $c = O(\log_y nx)$ (in particular, $c = O(\log n)$ for any fixed x and y) such that for all n-vertex m-edge graphs of edge-connectivity greater than c,*

$$T(G; x, y) = \frac{y^m}{(y-1)^{n-1}}(1 + O(1/n)).$$

Thus, a good approximation can be given in constant time by ignoring G and returning the constant $y^m/(y-1)^{n-1}$. Note that almost all graphs fall under this theorem as the minimum cut of a random graph is tightly concentrated around $n/2 \gg c$.

Theorem 6.2. *For every $y > 1$ there is a $c = O(y \log_y nx)$ such that there is an FPRAS for $T(G; x, y)$.*

This theorem is perhaps unsurprising given the previous theorem. But it is not immediate since the input may specify $\epsilon \ll 1/n$. A slightly more challenging quantity is the "second-order term" saying how far a given graph diverges from its approximation in the first theorem.

Theorem 6.3. *Let*

$$\Delta T(G; x, y) = \frac{y^m}{(y-1)^{n-1}} - T(G; x, y).$$

For any fixed $y > 1$ and fixed x, there is a $c = O(\log n)$ such that there is an FPRAS for $\Delta T(G; x, y)$.

This theorem is stronger than and implies the previous theorem. When ΔT is very close to 0, $\frac{y^m}{(y-1)^{n-1}}$ accurately approximates T but approximating ΔT with small relative error is harder.

6.2 Method

Our proofs begin with a lemma of Alon, Frieze, and Welsh [1] (which we have slightly rephrased to include what is for them the special case of $x = 1$).

Lemma 6.4 (see [1]). *When $y > 1$,*

$$T(G; x, y) = \frac{y^m}{(y-1)^{n-1}} E[Q^{\kappa-1}],$$

where $Q = (x-1)(y-1)$ and κ is a random variable equal to the number of connected components of G when each edge of G fails independently with probability $p = 1/y$. (In the case $Q = 0$ (when $x = 1$), we use the fact that $0^r = 0$ for $r \neq 0$ while $0^0 = 1$.)

In other words, when p_r is the probability that the graph with random edge failures partitions into exactly r components, the Tutte polynomial can be evaluated from

$$E[Q^{\kappa-1}] = \sum_{k=1}^{n} p_r Q^{r-1}.$$

For the remainder of this section, we normalize our analysis by considering the quantity $T'(G; x, y) = T(G; x, y)\frac{(y-1)^{n-1}}{y^m} = E[Q^{\kappa-1}]$. Clearly, any results on relative approximations to T' translate immediately into results on relative approximations to T.

We begin with an intuitive argument. From Theorem 2.9, when $p^c = n^{-(2+\delta)}$ (which happens for some $c = O(\log n)$ for any fixed p) we know p_r is negligible for $r \geq 1$. Intuitively, since $p_1 \approx 1$ and all other $p_r \approx 0$, we might as well approximate T' by Q. Extending this argument, we know that compared to p_2, all terms p_r for $r > 2$ are negligible. Therefore, the error in the approximation of T' by Q is almost entirely determined by $p_2 Q^2$, which we can determine by computing p_2.

To prove our results formally, we have to deal with the fact that the term Q^r in the expectation increases exponentially with r. We prove that the p_r decay fast enough to damp out the increasing values of Q^r. We also need to be careful that when $Q < 0$, the large leading terms do not cancel each other out.

6.3 Proofs

For our formal analysis, instead of the quantities p_r, it is more convenient to work with quantities s_r measuring the probability that the graph partitions into r *or more* components. Note that $s_1 = 1$ and $s_2 = \text{FAIL}(p)$. Since $p_r = s_r - s_{r+1}$, it follows that

$$\begin{aligned}
T'(G;x,y) &= \sum_{r=1}^{n} p_r Q^{r-1} \\
&= \sum_{r=1}^{n} (s_r - s_{r+1}) Q^{r-1} \\
&= \sum_{r=1}^{n} s_r Q^{r-1} - \sum_{r=2}^{n} s_r Q^{r-2} \\
&= 1 + \sum_{r=2}^{n} s_r (Q^{r-1} - Q^{r-2}) \\
&= 1 + (Q-1) \sum_{r=2}^{n} s_r Q^{r-2}.
\end{aligned}$$

Theorem 6.1 will follow directly from the last equation if we can show that the trailing term $(Q-1)\sum_{r=2}^{n} s_r Q^{r-2} = O(1/n)$. Theorem 6.3 will follow if we can give an FPRAS for $\sum_{r=2}^{n} s_r Q^{r-2}$. The fact that the value of this sum is $o(1)$ (Theorem 6.1) means that the FPRAS for it immediately yields an FPRAS for T', thus proving Theorem 6.2.

To prove these results, first consider the case $x = 1$. In this case $Q = 0$, meaning $Q^{r-2} = 1$ for $r = 2$ and 0 for $r > 2$. Thus $T'(G;x,y) = 1 - s_2 = 1 - \mathrm{FAIL}(p) = \mathrm{REL}(p)$. We have already seen in Theorem 2.9 that whenever $p^c = n^{-(2+\delta)}$, the probability that the graph becomes disconnected is at most $n^{-\delta}(1+2/\delta)$. This is certainly $O(1/n)$ if $\delta \geq 1$, meaning $\mathrm{REL}(p) = 1 - O(1/n)$. But this in turn is true when $p^c < n^{-3}$, i.e.,

$$c > 3 \log_y n$$

This proves Theorem 6.1 for $Q = 0$. On the other hand, Theorem 6.3 simply claims that there is an FPRAS for $1 - \mathrm{REL}(p) = \mathrm{FAIL}(p)$, which is what Section 2 showed. Finally, Theorem 6.2 says that when $\mathrm{FAIL}(p)$ is small, we can approximate $\mathrm{REL}(p)$ (by approximating $\mathrm{FAIL}(p)$).

We now generalize this argument to the case $x > 1$. To derive the appropriate lower bound on c, we state two criteria that will we need in our analysis. First, we require c to be such that $p^c = n^{-(2+\delta)}$ for some $\delta > 1$. Equivalently, we have $1 < \delta = -\log(n^2 p^c)/\log n$. Second, we require that $Q < \frac{1}{4} n^{\delta/4}$. Plugging in for δ, we find the equivalent requirement

$$\begin{aligned}
Q &< \frac{1}{4} n^{\delta/4} \\
&= \frac{1}{4} (n^2 p^c)^{-1/4} \\
(4Q)^4 &< 1/n^2 p^c \\
n^2 (4Q)^4 &< y^c \\
\log_y(256 Q^4 n^2) &< c
\end{aligned}$$

This is true for some $c = O(\log_y(nQ)) = O(y \ln nx)$ as claimed.

Given the above relations between Q, n, and δ, we can use Corollary 4.8. Since $p^c = n^{-(2+\delta)}$, we deduce that $s_r \leq n^{-r\delta/2}$. Since $Q < \frac{1}{4}n^{\delta/4} < \frac{1}{2}n^{\delta/2}$ we find that

$$\begin{aligned}
\sum_{r=r_0}^{n} s_r Q^{r-2} &\leq Q^{-2} \sum_{r \geq r_0} (Qn^{-\delta/2})^r && (1)\\
&\leq Q^{-2}(Qn^{-\delta/2})^{r_0}/(1 - (Qn^{-\delta/2})^{r_0})\\
&\leq Q^{-2}(Qn^{-\delta/2})^{r_0}/(1 - \frac{1}{2^{r_0}})\\
&\leq 2Q^{-2}(Qn^{-\delta/2})^{r_0}
\end{aligned}$$
$$(2)$$

Our results follow from this bound. First, taking $r_0 = 2$, we find that the error in approximating $T'(G; x, y)$ by 1 is at most

$$2n^{-\delta} = o(1).$$

This proves Theorem 6.1.

To prove Theorem 6.3, note that the leading term in the summation (1) is $s_2 \geq n^{-(2+\delta)}$. We can therefore estimate the sum to within relative error $O(\epsilon)$ by evaluating summation terms up to summation index r_0 where $(Qn^{-\delta/2})^{r_0} \leq \epsilon n^{-(2+\delta)}$. Since the left-hand side decreases exponentially in n as a function of r_0, we can achieve this error bound by taking

$$r_0 = O(\log_n(n^{2+\delta}/\epsilon)) = O(1 + \log_n 1/\epsilon).$$

In other words, we only need to determine $O(1 - \log_n \epsilon)$ terms in the summation. This in turn reduces to determining the quantities s_r appearing in those terms.

We cannot find the s_r exactly. However, for an ϵ-approximation, it suffices to approximate each relevant s_r to within ϵ. We can do so using the algorithm of Corollary 4.5. The running time of this algorithm for estimating the r-way failure probability to within ϵ is $(n^r/\epsilon)^{O(1)}$. We have argued above that we only need to run the algorithm for $r \leq r_0 = O(1 - \log_n \epsilon)$. It follows that the running time of our algorithm is $n^{O(1-\log_n \epsilon)}/\epsilon^{O(1)} = (n/\epsilon)^{O(1)}$, as required. This proves Theorem 6.3.

Finally, we consider the case $x < 1$. Our argument is essentially unchanged from before. We need to be slightly more careful because our sum is now an alternating sum, which means that the leading terms are a good approximation only if they do not cancel each other out. To see that such cancelling does not occur, note that the first term has value $s_2 = n^{-(2+\delta)}$, while the remaining terms (by the analysis above) have total (absolute) value $O(n(Qn^{-3\delta/2}))$. If we choose n large enough that $Q < \frac{1}{4}n^{\delta/4}$, then this bound is $O(\frac{1}{4}n^{-5\delta/4}) < \frac{1}{4}s_2$ for $\delta > 4$, so the remaining terms do not cancel s_2.

7 Conclusion

We have given an FPRAS for the all-terminal network reliability problem and several variants. In the case of large failure probability, the FPRAS uses straightforward Monte Carlo simulation. For smaller failure probabilities, the FPRAS uses an efficient reduction to DNF counting or a less efficient deterministic computation. An obvious open question is whether there is also a deterministic PAS for the case of large failure probabilities. Another is whether there is also an FPRAS for $\mathrm{REL}(p) = 1 - \mathrm{FAIL}(p)$, the question being open only for the case $\mathrm{REL}(p)$ near 0.

This work has studied probabilistic *edge* failures; a question of equal importance is that of network reliability under *vertex* failures. We are aware of no results on the structure of minimum vertex cuts that could lead to the same results as we have derived here for edge cuts. In particular, graphs can have exponentially many minimum vertex cuts. The same obstacle arises in *directed* graphs (where we wish to measure the probability of failing to be strongly connected).

Although the polynomial time bounds proven here are not extremely small, we expect much better performance in practice since most graphs will not have the large number of small cuts assumed for the analysis. Preliminary experiments [16] have suggested that this is indeed the case.

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