Defect Tolerance: Fundamental Limits and Examples

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***Abstract*—To be considered for the 2016 IEEE Jack Keil Wolf ISIT Student Paper Award. This paper addresses the problem of adding redundancy to a collection of physical objects so that the overall system is more robust to failures. Physical redundancy can (generally) only be achieved by employing copy/substitute procedures. This is fundamentally different from information redundancy, where a single parity check simultaneously protects a large number of data bits against a single erasure. We propose a bipartite graph model of designing defect-tolerant systems where defective objects are repaired by reconnecting them to strategically placed redundant objects. The fundamental limits of this model are characterized under various asymptotic settings and both asymptotic and finite-size optimal systems are constructed.**

Mathematically, we say that a k by m bipartite graph corrects t defects over alphabet of size q if for every q-coloring of k left vertices there exists a coloring of m right vertices such that every left vertex is connected to at least t same-colored right vertices. We study the tradeoff between redundancy m/k and the total number of edges in the graph divided by k. The question is trivial when $q \geq k$: the optimal solution is a simple t-fold replication. However, when $q < k$ some non-trivial savings are possible by leveraging the inherent repetition of colors.

***Index Terms*—defect-tolerant circuits, bipartite graphs, combinatorics, worst-case**

I. Introduction

Classical Shannon theory established principles of adding redundancy to data for combatting noise and, dually, of removing redundancy from data for more efficient storage. The central object of the classical theory is information, which unlike physical objects, can be freely copied and combined. In fact, the marvel of error-correcting codes is principally based on the counter-intuitive property that multiple unrelated information bits $X_1, \ldots, X_k$ can be simultaneously protected by adding "parity-checks" such as

$$Y = X_1 + \cdots + X_k \mod 2\,. \tag{1}$$

In this example, the added parity-check Y allows the recovery of the original message even if vector

$$(X_1, X_2, \ldots, X_k, Y)$$

undergoes an erasure of an arbitrary element.

Physical objects (e.g. servers in a data center) may also be subject to erasures (failures) and thus it is natural to ask about ways of insuring the system against probable failure events. Necessarily, any such solution would entail addition of spare (redundant) elements. Note, however, that for physical objects operations such as (1) are meaningless: generally the only operations that apply to physical objects are copy/substitute. It may, therefore, seem that nothing better than a simple replication can guard against failures. This paper shows otherwise. Indeed, there exist non-trivial ways to add redundancy as long as the objects' diversity does not exceed their number. That is, if the number of types of objects is smaller than the total number of them.

Specifically, we study the following problem formulation: Given k objects ("functional nodes"), connect each one of them to some of the available m spares ("redundant nodes") in such a way that in the event that $t \geq 1$ of the objects fail (original or spares) the overall system can be made to function after a repair step. The repair step consists of replacing each failed functional node with one of the spares that it was connected to. The key restriction is that objects must be one of q types and the spares have to be programmed to one of the q types *before* the failure events are known. We are interested in minimizing the redundancy m/k and the number of connections to spare nodes.

In short, we are looking for a $k \times m$ bipartite graph with the property that for any q-coloring of the left nodes there is a q-coloring of the right nodes such that each of k nodes is connected to at least t nodes of its color. The goal is to trade off redundancy m/k vs. number of edges. It may be instructive to look at simple non-trivial graphs in Figures 3-4. (In all figures, circles are original or functional nodes and squares are spare or redundant nodes.)

We give several settings for which our model applies:

- Objects are servers (with q different types of hardware) in a data center. Spares have to be installed in the adjacent racks and the bipartite graph encodes possible reroutings of network ports.
- Objects are digital gates of one of q types on a silicon chip. Imperfect manufacturing process causes certain gates to fail. As part of post-manufacture testing a configurable interconnect fabric is programmed to route around defective gates. Note that here again, the spare gates need to have their type specified before the failures are known. This case is discussed further in Section II-B.
- For $q = 2$ our problem is equivalent to sparsity vs. edge-size tradeoff for (t, t)-colorable hypergraphs, cf. [1].

It is not hard to come up with other potential applications in warehouse planning, operations research, public safety etc.

To summarize our main findings, if the number of types $q \geq k$ then no strategy is better than straightforward t-fold replication. However, as long as $q < k$ there exists designs

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The research was supported by the Center for Science of Information (CSoI), and NSF Science and Technology Center, under grant agreement CCF-09-39370.

that provide savings compared to repetition, as we will see in Section III. Consequently, we characterize the fundamental tradeoff between redundancy m/k and the number of edges (connections) in the following cases: 1) q, t fixed and $k, m \to \infty$; 2) q fixed and $k, m, t \to \infty$; 3) q, k fixed and $m, t \to \infty$. Perhaps surprisingly, in this (combinatorial) problem it is possible to obtain exact answers for asymptotics.

II. Problem Setup and Main Results

A. Defect-tolerance model

Definition 1. *Fix finite alphabet $\mathcal{X}$ where $|\mathcal{X}| = q$. A bipartite graph with k functional (left) nodes and m redundant (right) nodes is called a t-*error correcting design *if for any labeling of k functional nodes by elements of $\mathcal{X}$ there exists a labeling of m redundant nodes by elements of $\mathcal{X}$ such that every functional node labeled $x \in \mathcal{X}$ has at least t neighbors labeled x. We will call such a graph a (k, m, t, E)-design, with E denoting the number of edges.*

This paper is devoted to the fundamental tradeoff between the two basic parameters of t-error correcting designs:

- redundancy of a (k, m, t, E)-design is $\rho = \frac{m}{k}$
- the wiring complexity (or average degree) of a (k, m, t, E)-design is $\varepsilon = \frac{E}{k}$

Definition 2. *For a fixed q and $t \geq 1$ we define the region $\mathcal{R}_t$ as the closure of the set of all achievable pairs of (ε, ρ):*

$$\mathcal{R}_t \triangleq \text{closure}\left\{\left(\frac{E}{k}, \frac{m}{k}\right) : \exists (k, m, t, E)\text{-}design\right\} \tag{2}$$

Proposition 1. *(Properties of $\mathcal{R}_t$)*

1) *$(\varepsilon, \rho) \in \mathcal{R}_t$ iff there exists a sequence of (k, m, t, E)-designs with $\frac{E}{k} \to \varepsilon$, $\frac{m}{k} \to \rho$ as $k, m \to \infty$;*
2) *if $(\varepsilon, \rho) \in \mathcal{R}_t$ and $\varepsilon' \geq \varepsilon, \rho' \geq \rho$ then $(\varepsilon', \rho') \in \mathcal{R}_t$;*
3) *$\mathcal{R}_t$ are closed convex subsets of $\mathbb{R}_+^2$;*
4) *We have*

$$\limsup_{t\to\infty} \frac{1}{t}\mathcal{R}_t = \text{closure}\left\{\bigcup_{t\geq 1} \frac{1}{t}\mathcal{R}_t\right\} \triangleq \mathcal{R}_\infty\,, \tag{3}$$

5) *Limiting region $\mathcal{R}_\infty$ is also a closed convex subset of $\mathbb{R}_+^2$ characterized as*

$$\mathcal{R}_\infty \triangleq \text{closure}\left\{\left(\frac{E}{kt}, \frac{m}{kt}\right) : \exists (k, m, t, E) - design\right\} \tag{4}$$

B. Reconfigurable defect-tolerant circuits

To interpret the relation between Definition 1 and defect-tolerance we consider one particular application, namely reconfigurable circuits. Consider a chip design process, in which a portion of the chip is composed of many similar cells. Each cell has k input/output buses and k placeholders (nodes) that can be filled in with logic realizing one of q functions. Now because of manufacturing defects, not all k functional elements will operate correctly. For this reason, each cell also contains m placeholders for redundant elements. The designer then selects what type of logic to instantiate into these redundant elements. Once the chip is manufactured and placed on the testbed, the testing equipment goes over each cell and checks which functional elements came out defective. The programmable switches then can be used to reconnect input/output buses from the defective functional elements to one of the redundant nodes containing the same logic.

With respect to this application, the goal is to explain how many redundant elements and provisional wires (buses) each cell needs to contain and also to construct optimal interconnects. The exact relation to the previous definition of the t-error correcting design is as follows: the k functional nodes in our model represents the placeholders intended for the components which are necessary for the chip to operate and the redundant nodes represents the placeholders for the redundant components. The labeling we apply to the nodes is the choice of components to each space. The edges correspond to the provisional wires.

Proposition 2. *An interconnect for a reconfigurable circuit can tolerate any t manufacturing defects for any choice of functional nodes if and only if the interconnect is a t-error correcting design.*

Note that our performance metrics, ρ and ε, are meaningful for this circuit interpretation: they correspond to the extra silicon area and wiring required for defect-tolerance. Several natural questions arise in regards to Definition 1 and defect-tolerance in circuits. For example, it would be natural to allow the design (interconnect) to depend on the particular functional node labeling. This and other variations will be discussed in Section VI.

Relation to prior work: The subject of designing digital electronics robust to errors has been traditionally approached with the goal of combatting dynamic noise. This is epitomized in the large body of work started by von Neumann [2]. Although significant progress has been made in understanding fundamental limits in von Neumann's model, the practical applications are limited due to a prohibitively high level of redundancy required [3].

Here, instead, we are interested in fighting static manufacturing failures. This brings the advantage of being able to test which parts of the circuit failed and to configure out (or "wire around") the defective parts. This side information enables significant savings in redundancy [4]. In fact, it is rather popular in practice: multi-core CPUs [5], analog-to-digital converters [6], sense-amplifiers [7], parallel computing [8], [9], etc.

In summary, fighting dynamic noise (von Neumann's model) has good theoretical understanding, but requires huge redundancy. Static defects are practically handled via reconfigurability. This paper is an attempt to provide theoretical foundations for the latter method.

C. Overview of two main results

The two main results that characterize the redundancy-wiring complexity tradeoff are for the small t case (Theorems 3 and 4) and the asymptotic t case (Theorem 5). The resulting achievable regions for $q = 2$ are plotted in Figure 1.

Theorem 3. *When $q = 2$, for $t = 1$ and $t = 2$, we have*

$$\mathcal{R}_t = \{(\varepsilon, \rho) : \varepsilon \geq t \text{ and } \varepsilon \geq 2t - \rho\} \tag{5}$$

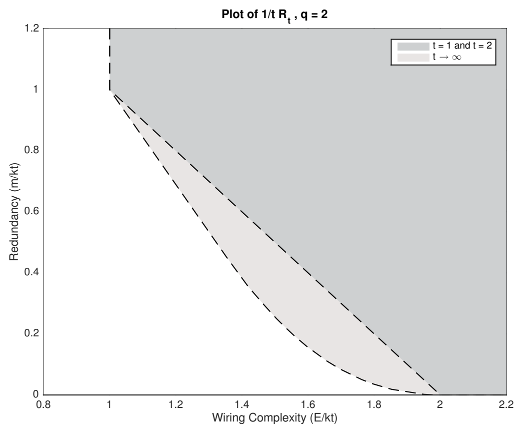


Fig. 1. Achievable regions for redundancy and wiring complexity tradeoff when $q = 2$. Regions $\mathcal{R}_1$ and $\frac{1}{2}\mathcal{R}_2$ are shown in darker gray. Region $\mathcal{R}_\infty$ includes lighter and darker gray areas. All other regions $\frac{1}{t}\mathcal{R}_t$ lie between $\mathcal{R}_1$ and $\mathcal{R}_\infty$.

Theorem 4. *For $q = 3$ and $t = 1$ we have*

$$\mathcal{R}_1 = \{(\varepsilon, \rho) : \varepsilon \geq 3 - 2\rho, \rho \geq 0\} \tag{6}$$

Theorem 5. *Fix q. The region $\mathcal{R}_\infty$ defined in (3) is the closure of the set of points $(\tilde{\varepsilon}, \tilde{\rho})$, parameterized by the distribution P_S with a finite support on $\mathbb{Z}_+$, and*

$$\tilde{\varepsilon} = \frac{\mathbb{E}\,[S]}{F(P_S)}, \quad \tilde{\rho} = \frac{1}{F(P_S)}, \tag{7}$$

$$F(P_S) \triangleq \min_{P_X} \max_{P_{Y|\underline{L}}} \min_{j \in [q]} \frac{1}{P_X(j)} \mathbb{E}\,[L_j 1\{Y = j\}] \tag{8}$$

where $\mathbb{E}\,[\cdot]$ is computed over random variables $S \in \mathbb{Z}_+, X \in [q], \underline{L} = (L_1, \ldots, L_q) \in \mathbb{Z}_+^q, Y \in [q]$ with joint distribution

$$P_{S,\underline{L},Y}(s, \underline{\ell}, y) \triangleq P_S(s) P_{\underline{L}|S}(\underline{\ell}|s) P_{Y|\underline{L}}(y|\underline{\ell}). \tag{9}$$

where

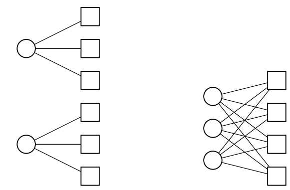
$$P_{\underline{L}|S}(\underline{\ell}|s) \triangleq \binom{s}{\ell_1, \cdots, \ell_q} \prod_{j=1}^{q} P_X(j)^{\ell_j}. \tag{10}$$

The optimal designs for Theorem 5 are what we call *subset designs*, which are discussed in Section III-B. Note that evaluation of the bound (7) presents non-trivial technical difficulties. The proofs of Theorems 3 and 5 are given in Sections IV and V respectively. See Section IV of [10] for Theorem 4.

D. Implications and extensions of results

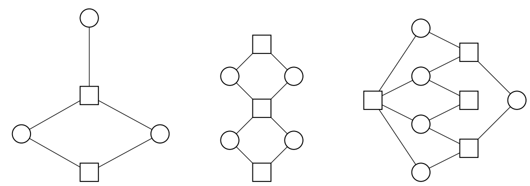
The result for $\mathcal{R}_1$ and $\mathcal{R}_2$ demonstrates that for correcting small numbers of defects the best solution in the limit of a large number of functional nodes is a linear combination of two basic designs, the repetition block and the complete design (see Figure 2), and designs with finite k can do no better.

We note that while we do not know $\mathcal{R}_t$ for $t > 2$, according to (4) all regions $\frac{1}{t}\mathcal{R}_t$ will lie between $\mathcal{R}_1$ and $\mathcal{R}_\infty$, approaching the latter as $t \to \infty$, making Theorem 5 the fundamental limit for the tradeoff between redundancy and wire complexity. It is perhaps surprising that unlike most known asymptotic combinatorial problems, this one admits a relatively simple solution.



(a) Repetition block (b) Complete design

Fig. 2. Two elementary designs.



(a) $q = 2$ (b) $q = 3$ (c) $q = 4$

Fig. 3. Smallest non-trivial 1-error correcting designs.

Theorem 5 also holds for arbitrary alphabet, whereas computing regions $\mathcal{R}_t$ for large q is not covered by Theorem 3 or 4. In particular the proof of Theorem 4 requires finer arguments on graph structures.

We also study asymptotics in the regime of fixed k and $m, t \to \infty$ (see [10] Section V). In all results, there is an optimal set of designs where the functional nodes have regular degree.

III. Examples of Good Designs

The two most basic designs are the following:

1) *Repetition blocks:* Each functional node has t private redundant nodes (See Figure 2(a).) Corrects t errors.
2) *Complete designs:* Fully connected bipartite graph with qt redundant nodes. (See Figure 2(b).) Corrects t errors (just program redundant nodes to hold t-copies of each value in $\mathcal{X}$).

As $k \to \infty$ the complete design achieves $\varepsilon = qt$ and $\rho = 0$, which is clearly the best possible.

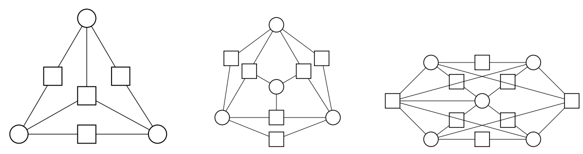
A. Smallest non-trivial designs

If $k \leq q$ then all functional nodes can have different values and thus one is forced to use the repetition block to correct t errors. For $k = q + 1$ the question becomes more interesting. First, notice that the minimal possible m equals qt, like in the complete design. However, some of the edges can be removed. Optimal designs with $k = q + 1$, $m = q$ and $t = 1$ are shown in Figure 3. Optimal designs with $k = q + 1$, $m = 2q$ and $t = 2$ are shown in Figure 4. None of these designs are *asymptotically* optimal in terms of the ρ-ε tradeoff.

B. Subset designs

$S(k, s)$ is a bipartite graph with k functional nodes and $m = \binom{k}{s}$ redundant nodes, each connected to a distinct s-subset of $\{1, \ldots, k\}$. In general, we allow subset designs to have multiple and possibly different subset sizes. We need the following idea to make this precise.

Proposition 6 (Merging)**.** *Consider (k, m_j, t_j, E_j)-designs G_j. The merging of G_j, denoted $G = \bigvee_j G_j$ is a graph formed*



(a) $q=2$ (b) $q=3$ (c) $q=4$

Fig. 4. Smallest non-trivial 2-error correcting designs.

by taking disjoint copies of G_j and identifying functional nodes. G is a $(k, \sum_j m_j, \sum_j t_j, \sum_j E_j)$-design.

Definition 3 (Subset design)**.** *Given k and positive integers $s_1, s_2, \ldots, s_r \in [k]$, $S(k,s_1) \vee S(k,s_2) \vee \cdots \vee S(k,s_r)$ is a subset design with k functional nodes and $m = \sum_{j=1}^{r} \binom{k}{s_j}$ redundant nodes.*

For example, the Hamming block, Figure 4(a), is $S(3,2) \vee S(3,3)$, the repetition block is $S(k,1) \vee \cdots \vee S(k,1)$ (t times) and complete design is $S(k,k) \vee \cdots \vee S(k,k)$ (qt times).

Subset designs are the unique designs where there exists a group of bipartite-graph automorphisms that acts as the full symmetric group S_k on functional nodes. The next proposition gives an estimate on the performance of subset designs. (See [10] Section V for exact statement.)

Proposition 7. *(Informal) Fix $\mathcal{X}$, $q = |\mathcal{X}|$ and $k \in \mathbb{Z}$. If G is a subset graph with proportion of degree s redundant nodes given by P_S, k functional nodes, and m redundant nodes, then G has $E = m\mathbb{E}[S]$ edges and G can correct*

$$t \approx \frac{m}{k} F(P_S) \tag{11}$$

errors.

Proof Sketch. To show $t \approx \frac{m}{k}F(P_S)$, fix any labeling $w^k \in \mathcal{X}^k$ of the k functional nodes of G. Let r^m to be the optimal labeling of the redundant nodes. Let

- P_X denote the empirical distribution of the frequency of each label in w^k
- $\underline{\ell} = (\ell_1, \cdots, \ell_q)$ be the *type* of each redundant node v, where ℓ_j is the number of functional nodes with label j which is a neighbor of redundant node v
- $P_{Y|\underline{L}}(j|\underline{\ell})$ be the proportion (empirical distribution) of redundant nodes of type $\underline{\ell}$ which are labeled j in labeling r^m

The distribution of $\underline{\ell}$ for degree s redundant nodes is approximately given by (10). For each label j, we can count the *average* number of redundant node neighbors with label j a functional node with label j has. This quantity is given by (8) without the maximums and minimums, which we get after taking the worse case label j and P_X with the best possible $P_{Y|\underline{L}}(j|\underline{\ell})$. We can show there is a way for r^m to obtain this average for each functional node by random coding. □

IV. Bounds for finite t

A. Elementary achievability

Proposition 8. *The following region is achievable for any $t \geq 1$ and $q \geq 2$:*

$$\mathcal{R}_t^{(K)} \triangleq \{(\varepsilon,\rho) : \varepsilon \geq qt + (1-q)\rho, \varepsilon \geq t, \rho \geq 0\} \tag{12}$$

Proof. Note that corner points (t,t) and $(qt,0)$ are achieved by the repetition block and the complete design, respectively. By Proposition 1 the region $\mathcal{R}_t$ is convex and hence must contain $\mathcal{R}_t^{(K)}$. □

By merging the repetition block and complete design, we can get designs in $\mathcal{R}_t^{(K)}$ with each functional node having the same degree.

B. Covering converse

Theorem 9. *Fix $\mathcal{X}$, $q = |\mathcal{X}|$ and suppose $(\varepsilon,\rho) \in \mathcal{R}_t$. Then there exists $\pi_t, \pi_{t+1}, \ldots, \pi_{qt} \geq 0$ satisfying*

$$\sum_{j=t}^{qt} j\pi_j \leq \varepsilon, \quad \sum_{j=t}^{qt} \pi_j = 1 \tag{13}$$

$$\sum_{j=t+1}^{qt} \pi_j \log_q \lfloor j/t \rfloor \geq 1 + (t-1)\pi_t - \rho\,. \tag{14}$$

Proof. Notice that every functional node clearly should have degree at least t. Let us define $\pi_j, j = t, t+1, ..., qt-1$ to be the fraction of functional nodes of degree j and π_{qt} to be the fraction with degree qt or larger. This satisfies (13). We only need to show (14).

For each labeling $r^m \in \mathcal{X}^m$ of redundant nodes let $\mathcal{G}_t(r^m)$ be the set of functional node labelings for which conditions of Definition 1 are satisfied (we say that r^m covers $\mathcal{G}_t(r^m)$ of the labelings). It is clear that the design is t-error correcting if and only if

$$\bigcup_{r^m \in \mathcal{X}^m} \mathcal{G}_t(r^m) = |\mathcal{X}|^k = q^k\,. \tag{15}$$

Two functional nodes of degree t should have disjoint neighborhoods (otherwise labeling them different values clearly violates Definition 1). Thus $\mathcal{G}_t(r^m)$ is empty unless each such neighborhood has a constant label. This shows that for the $tk\pi_t$ redundant nodes we are restricted to only $q^{k\pi_t}$ choices, while the rest contribute $q^{m-tk\pi_t}$ more choices.

Given any of the $q^{m-(t-1)k\pi_t}$ choices of r^m we can estimate $|\mathcal{G}_t(r^m)|$ from above by assuming that each functional node of degree d can take any of the $\lfloor d/t \rfloor$ values in $\mathcal{X}$ while still satisfying the t-wise coverage condition of Definition 1. This yields

$$|\mathcal{G}_t(r^m)| \leq \prod_{j=t}^{qt} \lfloor j/t \rfloor^{k\pi_j}\,, \tag{16}$$

and thus applying the union bound to (15), we get (14). □

Proof of Theorem 3. Achievability follows from Proposition 8. The converse is given by evaluating the optimal ε for each ρ with the constraints given in (13)-(14) for $t = 1, 2$. □

Remark 1. *The bound given by Theorem 9 is the best bound of $\mathcal{R}_t$ known to us for values of ε near qt.*

V. Fundamental limit for $t \to \infty$

A. Converse and proof outline

Proposition 10 (Symmetrization Converse)**.** *If there exists a (k,m,t,E)-design then there exists a $(k, m \cdot k!, t \cdot k!, E \cdot k!)$-design which is a subset design (Definition 3).*

Proof. Let G be a (k, m, t, E)-design. Choose an ordering of the functional nodes in G. For each $\sigma \in S_k$ (the full symmetric group on k elements), let G_σ be isomorphic to the design G, with the order of its functional nodes transformed by σ. Then merge G_σ for all $\sigma \in S_k$ identifying functional nodes with the same order, so that the result is

$$G_{\mathrm{PERM}} = \bigvee_{\sigma \in S_k} G_\sigma \,. \tag{17}$$

G_{PERM} is constructed to be permutation invariant (and thus a subset design) and by Proposition 6 G_{PERM} is a $(k, m \cdot k!, t \cdot k!, E \cdot k!)$-design. □

In terms of normalized values $\frac{E}{kt}, \frac{m}{kt}$ every design on k functional nodes is equivalent to a subset design on k functional nodes.

Proof Sketch. Proof of Theorem 5

Achievability: Given by Proposition 7. *Converse*: For any design G which is a (k, m, t, E)-design, there exists a subset design G' which is a $(k, m \cdot k!, t \cdot k!, E \cdot k!)$-design by Proposition 10. If P_S are the proportions of degree s redundant nodes in G', then by Proposition 7, we get $t \cdot k! \le \frac{m \cdot k!}{k} F(P_S)$, bounding the performance of G. □

VI. Discussion

A. Comparison to other models for defect tolerance

This paper studies a defect-tolerance model where steps proceed as follows:

a. bipartite graph is designed;
b. functional nodes get q-ary labeling;
c. redundant nodes are assigned q-ary labels (so that each functional node has t neighbors with matching label).

There are two natural variations where sequence of steps are interchanged:

- *adaptive graph*: b.→a.→c.
- *non-adaptive redundancy*: a.→c.→b.

In the first case, the graph is a function of the q-ary labels, while in the second case the redundant nodes are not allowed to depend on the labeling of functional nodes. The setting considered in this paper (a.→b.→c.) is an intermediate case.

The fundamental redundancy-wiring complexity tradeoff for these cases is defined similarly to (2). Both tradeoffs are rather easy to determine for any $t \ge 1$:

- *adaptive graph*: $\mathcal{R}_t = \{(\varepsilon, \rho) : \varepsilon \ge t, \rho \ge 0\}$.
- *non-adaptive redundancy*: $\mathcal{R}_t = \{(\varepsilon, \rho) : \varepsilon \ge qt, \rho \ge 0\}$.

These observations are summarized in Figure 5.

B. Stochastic defects

This work considers correcting arbitrary (worst-case) defect patterns. One of the conclusions is that to correct fraction α of defects (i.e. $t = \alpha k$) on k functional nodes, the number of edges should grow as k^2. It is natural to ask what happens if instead we relaxed the requirement to correcting i.i.d. Bernoulli(α) defects. Each defect pattern will occur with some probability and we only want all defects in the design to be corrected with high probability (computed over distribution of defects and functional labels). It turns out that in such a probabilistic model, correcting fraction-α of defects is possible with designs possessing $O(k \log k)$ edges and $O(k)$ redundant nodes. See Section 4.4 in [11].

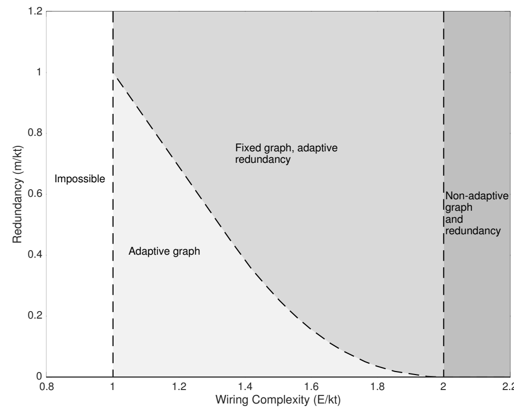


Fig. 5. Comparison of redundancy-wiring complexity tradeoffs for different levels of adaptivity when $q = 2$.

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