

A SEMI-EXACT DEGREE CONDITION FOR HAMILTON CYCLES IN DIGRAPHS

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ABSTRACT. We show that for each $\beta > 0$, every digraph G of sufficiently large order n whose outdegree and indegree sequences $d_1^+ \leq \dots \leq d_n^+$ and $d_1^- \leq \dots \leq d_n^-$ satisfy $d_i^+, d_i^- \geq \min\{i + \beta n, n/2\}$ is Hamiltonian. In fact, we can weaken these assumptions to

(i) $d_i^+ \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^- \geq n - i$;

(ii) $d_i^- \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^+ \geq n - i$;

and still deduce that G is Hamiltonian. This provides an approximate version of a conjecture of Nash-Williams from 1975 and improves a previous result of Kühn, Osthus and Treglown.

1. INTRODUCTION

The decision problem of whether a graph contains a Hamilton cycle is one of the most famous NP-complete problems, and so it is unlikely that there exists a good characterization of all Hamiltonian graphs. For this reason, it is natural to ask for sufficient conditions which ensure Hamiltonicity. The most basic result of this kind is Dirac's theorem [6], which states that every graph of order $n \geq 3$ and minimum degree at least $n/2$ is Hamiltonian.

Dirac's theorem was followed by a series of results by various authors giving even weaker conditions which still guarantee Hamiltonicity. An appealing example is a theorem of Pósa [20] which implies that every graph of order $n \geq 3$ whose degree sequence $d_1 \leq d_2 \leq \dots \leq d_n$ satisfies $d_i \geq i + 1$ for all $i < n/2$ is Hamiltonian. Finally, Chvátal [4] showed that if the degree sequence of a graph G satisfies $d_i \geq i + 1$ or $d_{n-i} \geq n - i$ whenever $i < n/2$, then G is Hamiltonian. Chvátal's condition is best possible in the sense that for every sequence not satisfying this condition, there is a non-Hamiltonian graph whose degree sequence majorises the given sequence.

It is natural to seek analogues of these theorems for digraphs. For basic terminology on digraphs, we refer the reader to the monograph of Bang-Jensen and Gutin [2]. Ghouila-Houri [8] proved that every digraph of order n and minimum indegree and outdegree at least $n/2$ is Hamiltonian, thus providing such an analogue of Dirac's theorem for digraphs. Thomassen [21] asked the corresponding question for oriented graphs (digraphs with no 2-cycles). One might expect that a weaker minimum semidegree (i.e. indegree and outdegree) condition would suffice in this case. Häggkvist [9] gave a construction showing that a minimum semidegree of $\frac{3n-4}{8}$ is necessary and conjectured that it is also sufficient to guarantee a Hamilton cycle in any oriented graph of order n . This conjecture was recently proved in [11], following an asymptotic solution in [12]. In [5] we gave an NC algorithm for finding Hamilton cycles in digraphs with a certain robust expansion property which captures several previously known criteria for finding Hamilton cycles. These and other results are also discussed in the recent survey [17].

However, no digraph analogue of Chvátal's theorem is known. For a digraph G of order n , let us write $d_1^+(G) \leq \dots \leq d_n^+(G)$ for its outdegree sequence, and $d_1^-(G) \leq \dots \leq d_n^-(G)$ for its indegree sequence. We will usually write d_i^+ and d_i^- instead of $d_i^+(G)$ and $d_i^-(G)$ if this is unambiguous.

The following conjecture of Nash-Williams [19] would provide such an analogue.

Conjecture 1. *Let G be a strongly connected digraph of order $n \geq 3$ and suppose that for all $i < n/2$*

(i) $d_i^+ \geq i + 1$ or $d_{n-i}^- \geq n - i$;

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- (ii) $d_i^- \geq i + 1$ or $d_{n-i}^+ \geq n - i$.

Then G contains a Hamilton cycle.

Nash-Williams also highlighted the following conjectural analogue of Pósa's theorem, which would follow from Conjecture 1.

Conjecture 2. *Let G be a digraph of order $n \geq 3$ such that $d_i^+, d_i^- \geq i + 1$ for all $i < (n - 1)/2$ and $d_{\lceil n/2 \rceil}^+, d_{\lceil n/2 \rceil}^- \geq \lceil n/2 \rceil$. Then G contains a Hamilton cycle.*

Note that in Conjecture 2 the degree condition implies that G is strongly connected. It is not even known whether the above conditions guarantee the existence of a cycle though any given pair of vertices (see [3]). We will prove the following semi-exact form of Conjecture 2. It is 'semi-exact' in the sense that for half of the vertex degrees, we obtain the conjectured bound, whereas for the other half, we need an additional error term.

Theorem 3. *For every $\beta > 0$ there exists an integer $n_0 = n_0(\beta)$ such that the following holds. Suppose G is a digraph on $n \geq n_0$ vertices such that $d_i^+, d_i^- \geq \min\{i + \beta n, n/2\}$ whenever $i < n/2$. Then G contains a Hamilton cycle.*

Recently, the following approximate version of Conjecture 1 for large digraphs was proved by Kühn, Osthus and Treglown [18].

Theorem 4. *For every $\beta > 0$ there exists an integer $n_0 = n_0(\beta)$ such that the following holds. Suppose G is a digraph on $n \geq n_0$ vertices such that for all $i < n/2$*

- (i) $d_i^+ \geq i + \beta n$ or $d_{n-i-\beta n}^- \geq n - i$;
(ii) $d_i^- \geq i + \beta n$ or $d_{n-i-\beta n}^+ \geq n - i$.

Then G contains a Hamilton cycle.

We will extend this to the following theorem, which implies Theorem 3.

Theorem 5. *For every $\beta > 0$ there exists an integer $n_0 = n_0(\beta)$ such that the following holds. Suppose G is a digraph on $n \geq n_0$ vertices such that for all $i < n/2$*

- (i) $d_i^+ \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^- \geq n - i$;
(ii) $d_i^- \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^+ \geq n - i$.

Then G contains a Hamilton cycle.

(For the purposes of our arguments it turns out that there is no significant difference in the use of the assumptions, so for simplicity the reader could just read our proof as it applies to Theorem 3.)

The improvement in the degree condition may at first appear minor, so we should stress that capping the degrees at $n/2$ makes the problem substantially more difficult, and we need to develop several new techniques in our solution. This point cannot be fully explained until we have given several definitions, but for the expert reader we make the following comment. Speaking very roughly, the general idea used in [12, 11, 5] is to apply Szemerédi's Regularity Lemma, cover most of the reduced digraph by directed cycles, and then use the expansion property guaranteed by the degree conditions on G to link these cycles up into a Hamilton cycle while absorbing any exceptional vertices. When the degrees are capped at $n/2$ two additional difficulties arise: (i) the expansion property is no longer sufficient to link up the cycles, and (ii) failure of a previously used technique for reducing the size of the exceptional set. Our techniques for circumventing these difficulties seem instructive and potentially useful in attacking Conjectures 1 and 2 in full generality.

Our paper is organized as follows. The next section contains some notation and Section 3 some preliminary observations and examples. Our proof will use the machinery of Szemerédi's Regularity Lemma, which we describe in Section 4. (Unlike [12, 11, 5], we do not require the Blow-up lemma.) Section 5 contains an overview of the proof in a special case that illustrates the

new methods that we introduce in this paper. The cycle covering result is proved in Section 6 and the proof of the special case completed in Section 7. In Section 8 we describe the structures that arise in the general case. We establish some bounds for these structures in Section 9. Our main theorem is proved in Section 10. The final section contains a concluding remark.

2. NOTATION

Given two vertices x and y of a digraph G , we write xy for the edge directed from x to y . The *order* $|G|$ of G is the number of its vertices. We write $N_G^+(x)$ and $N_G^-(x)$ for the outneighbourhood and inneighbourhood of x and $d_G^+(x)$ and $d_G^-(x)$ for its outdegree and indegree. The *degree* of x is $d_G(x) = d_G^+(x) + d_G^-(x)$. We usually drop the subscript G if this is unambiguous. The *minimum degree* and *maximum degree* of G are defined to be $\delta(G) = \min \{d(x) : x \in V(G)\}$ and $\Delta(G) = \max \{d(x) : x \in V(G)\}$ respectively. We define the *minimum indegree* $\delta^-(G)$ and *minimum outdegree* $\delta^+(G)$ similarly. The *minimum semidegree* is $\delta^0(G) = \min\{\delta^+(G), \delta^-(G)\}$. Given $S \subseteq V(G)$ we write $d_S^+(x) = |N^+(x) \cap S|$ for the outdegree of x in the set S . We define $d_S^-(x)$ and $d_S(x)$ similarly. Given a set A of vertices of G , we write $N_G^+(A)$ for the set of all outneighbours of vertices of A , i.e. for the union of $N_G^+(x)$ over all $x \in A$. We define $N_G^-(A)$ analogously.

Given vertex sets A and B in a graph or digraph G , we write $E_G(A, B)$ for the set of all edges ab with $a \in A$ and $b \in B$ and put $e_G(A, B) = |E_G(A, B)|$. As usual, we drop the subscripts when this is unambiguous. If $A \cap B = \emptyset$ we write $(A, B)_G$ for the bipartite subgraph of G with vertex classes A and B whose set of edges is $E_G(A, B)$. The restriction $G[A]$ of G to A is the digraph with vertex set A and edge set all those edges of G with both endpoints in A . We also write $G \setminus A$ for the digraph obtained by deleting A and all edges incident to it, i.e. $G \setminus A = G[V(G) \setminus A]$.

Cycles and paths will always be understood as directed cycles and directed paths, even if this is not explicitly stated. Given two vertices x and y on a directed cycle C we write xCy for the subpath of C from x to y . Similarly, given two vertices x and y on a directed path P such that x precedes y , we write xPy for the subpath of P from x to y . A *walk of length ℓ* in a digraph G is a sequence v_0, v_1, \dots, v_ℓ of vertices of G such that $v_i v_{i+1} \in E(G)$ for all $0 \leq i \leq \ell - 1$. The walk is *closed* if $v_0 = v_\ell$. A *1-factor* of G is a collection of disjoint cycles which cover all vertices of G . Given a 1-factor F of G and a vertex x of G , we write x_F^+ and x_F^- for the successor and predecessor of x on the cycle in F containing x . We usually drop the subscript F if this is unambiguous. We say that x and y are at *distance d* on F if they belong to the same directed cycle C in F and the distance from x to y or from y to x on C is d . Note in particular that with this definition, x and y could be at distance d and d' on F with $d \neq d'$.

A digraph G is *strongly connected* if for any ordered pair of vertices (x, y) there is a directed walk from x to y . A *separator* of G is a set S of vertices such that $G \setminus S$ is not strongly connected. We say G is *strongly k -connected* if $|G| > k$ and if it has no separator of size less than k . By Menger's theorem, this is equivalent to the property that for any ordered pair of vertices (x, y) there are k internally disjoint paths from x to y .

We write $a = b \pm c$ to mean that the real numbers a, b, c satisfy $|a - b| \leq c$. We sometimes also write an expression such as $d^\pm(x) \geq t$ to mean $d^+(x) \geq t$ and $d^-(x) \geq t$. The use of the \pm sign will be clear from the context.

To avoid unnecessarily complicated calculations we will sometimes omit floor and ceiling signs and treat large numbers as if they were integers.

3. PRELIMINARIES

In this section we record some simple consequences of our degree assumptions and describe the examples showing that Conjectures 1 and 2 would be best possible. We also recall two results on graph matchings and a standard large deviation inequality (the Chernoff bound).

Our degree assumptions are that for all $i < n/2$ we have

- (i) $d_i^+ \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^- \geq n - i$;
- (ii) $d_i^- \geq \min\{i + \beta n, n/2\}$ or $d_{n-i-\beta n}^+ \geq n - i$.

We claim that $\delta^+(G) = d_1^+ \geq \beta n$. For if this were false our assumptions would give $d_{n-1-\beta n}^- \geq n - 1$, i.e. G contains at least $\beta n + 1$ vertices of indegree $n - 1$. But a vertex of indegree $n - 1$ is an outneighbour of all other vertices, so this also implies that $\delta^+(G) \geq \beta n$. Similarly we have $\delta^-(G) \geq \beta n$.

To avoid complications with boundary cases it will be convenient to drop the condition $i < n/2$. We note that this does not change our assumptions. For if $n/2 \leq i < n - \beta n$ we can apply our assumption (i) to $i' = n - i - \beta n$ and get $d_{i'}^+ \geq \min\{i' + \beta n, n/2\}$ or $d_{n-i'-\beta n}^- \geq n - i'$, i.e. $d_{n-i-\beta n}^+ \geq n - i$ or $d_i^- \geq i + \beta n$, which implies assumption (ii) for i . Similarly assumption (ii) for i' implies assumption (i) for i . The assumptions do not make sense for $i \geq n - \beta n$, but if we consider any statement about d_j^\pm with $j \notin [1, n]$ as being vacuous (i.e. always true), then we do not have to impose any conditions when $i \geq n - \beta n$.

For an extremal example for Conjectures 1 and 2, consider a digraph G on n vertices constructed as follows. The vertex set is partitioned as $I \cup K$ with $|I| = k < n/2$ and $|K| = n - k$. We make I independent and K complete. Then we pick a set X of k vertices of K and add all possible edges in both directions between I and X . This gives a strongly connected non-Hamiltonian digraph G in which both the indegree and outdegree sequence are

$$\underbrace{k, \dots, k}_{k \text{ times}}, \underbrace{n-1-k, \dots, n-1-k}_{n-2k \text{ times}}, \underbrace{n-1, \dots, n-1}_{k \text{ times}}.$$

G fails conditions (i) and (ii) in Conjecture 1 for $i = k$ and also one of the conditions in Conjecture 2. In fact, a more complicated example is given in [18] where only one condition in Conjecture 1 fails. So, if true, Conjecture 1 would be best possible in the same sense as Chvátal's theorem.

A *matching* in a graph or digraph G is a set of pairwise disjoint edges. A *cover* is a set C of vertices such that every edge of G is incident to at least one vertex in C . For bipartite graphs these concepts are related by the following classical result of König.

Proposition 6. *In any bipartite graph, a maximum matching and a minimum cover have equal size.*

The following result, known as the ‘defect Hall theorem’, may be easily deduced from Proposition 6, using the observation that if C is a cover then $N(A \setminus C) \subseteq C \cap B$.

Proposition 7. *Suppose G is a bipartite graph with vertex classes A and B and there is some number D such that for any $S \subseteq A$ we have $|N(S)| \geq |S| - D$. Then G contains a matching of size at least $|A| - D$.*

We will also need the following well-known fact.

Proposition 8. *Suppose that J is a digraph such that $|N^+(S)| \geq |S|$ for every $S \subseteq V(J)$. Then J has a 1-factor.*

Proof. The result follows immediately by applying Proposition 7 (with $D = 0$) to the following bipartite graph Γ : both vertex classes A, B of Γ are copies of the vertex set of the original digraph J and we connect a vertex $a \in A$ to $b \in B$ in Γ if there is a directed edge from a to b in J . A perfect matching in Γ corresponds to a 1-factor in J . \square

We conclude by recording the Chernoff bounds for binomial and hypergeometric distributions (see e.g. [10, Corollary 2.3 and Theorem 2.10]). Recall that the binomial random variable with parameters (n, p) is the sum of n independent Bernoulli variables, each taking value 1 with probability p or 0 with probability $1 - p$. The hypergeometric random variable X with parameters (n, m, k) is defined as follows. We let N be a set of size n , fix $S \subset N$ of size $|S| = m$, pick a uniformly random $T \subset N$ of size $|T| = k$, then define $X = |T \cap S|$. Note that $\mathbb{E}X = km/n$.

Proposition 9. *Suppose X has binomial or hypergeometric distribution and $0 < a < 3/2$. Then $\mathbb{P}(|X - \mathbb{E}X| \geq a\mathbb{E}X) \leq 2e^{-\frac{a^2}{3}\mathbb{E}X}$.*

4. REGULARITY

The proof of Theorem 5 will use the directed version of Szemerédi's Regularity Lemma. In this section, we state a digraph form of this lemma and establish some additional useful properties. For surveys on the Regularity Lemma and its applications we refer the reader to [15, 13, 16].

4.1. The Regularity Lemma. The *density* of a bipartite graph $G = (A, B)$ with vertex classes A and B is defined to be $d_G(A, B) = \frac{e_G(A, B)}{|A||B|}$. We often write $d(A, B)$ if this is unambiguous. Given $\varepsilon > 0$, we say that G is ε -regular if for all subsets $X \subseteq A$ and $Y \subseteq B$ with $|X| \geq \varepsilon|A|$ and $|Y| \geq \varepsilon|B|$ we have that $|d(X, Y) - d(A, B)| < \varepsilon$. Given $d \in [0, 1]$, we say that G is (ε, d) -regular if it is ε -regular of density at least d . We also say that G is (ε, d) -super-regular if it is ε -regular and furthermore $d_G(a) \geq d|B|$ for all $a \in A$ and $d_G(b) \geq d|A|$ for all $b \in B$.

Given a digraph G , and disjoint subsets A, B of $V(G)$, we say that the ordered pair $(A, B)_G$ is ε -regular, if the corresponding undirected bipartite graph induced by the edges of G from A to B is ε -regular. We use a similar convention for super-regularity. The Diregularity Lemma is a version of the Regularity Lemma for digraphs due to Alon and Shapira [1]. We will use the degree form of the Diregularity Lemma, which can be easily derived from the standard version, in exactly the same manner as the undirected degree form. (See e.g. [16] for a sketch proof.)

Lemma 10 (Diregularity Lemma; Degree form). *For every $\varepsilon \in (0, 1)$ and each positive integer M' , there are positive integers M and n_0 such that if G is a digraph on $n \geq n_0$ vertices, $d \in [0, 1]$ is any real number, then there is a partition of the vertices of G into V_0, V_1, \dots, V_k and a spanning subdigraph G' of G with the following properties:*

- $M' \leq k \leq M$;
- $|V_0| \leq \varepsilon n, |V_1| = \dots = |V_k| =: m$ and $G'[V_i]$ is empty for all $0 \leq i \leq k$;
- $d_{G'}^+(x) > d_G^+(x) - (d + \varepsilon)n$ and $d_{G'}^-(x) > d_G^-(x) - (d + \varepsilon)n$ for all $x \in V(G)$;
- all pairs $(V_i, V_j)_{G'}$ with $1 \leq i, j \leq k$ and $i \neq j$ are ε -regular with density either 0 or at least d .

Note that we do not require the densities of $(V_i, V_j)_{G'}$ and $(V_j, V_i)_{G'}$ to be the same. We call V_1, \dots, V_k the *clusters* of the partition, V_0 the *exceptional set* and the vertices of G in V_0 the *exceptional vertices*. The *reduced digraph* $R = R_{G'}$ of G with parameters ε, d, M' (with respect to the above partition) is the digraph whose vertices are the clusters V_1, \dots, V_k and in which $V_i V_j$ is an edge precisely when $(V_i, V_j)_{G'}$ has density at least d .

In various stages of our proof of Theorem 5, we will want to make some pairs of clusters super-regular, while retaining the regularity of all other pairs. This can be achieved by the following folklore lemma. Here and later on we write $0 < a_1 \ll a_2$ to mean that we can choose the constants a_2 and a_1 from right to left. More precisely, there is an increasing function f such that, given a_2 , whenever we choose some $a_1 \leq f(a_2)$ all calculations in the proof of Lemma 11 are valid. Hierarchies with more constants are to be understood in a similar way.

Lemma 11. *Let $0 < \varepsilon \ll d, 1/\Delta$ and let R be a reduced digraph of G as given by Lemma 10. Let H be a subdigraph of R of maximum degree Δ . Then, we can move exactly $\Delta\varepsilon m$ vertices from each cluster V_i into V_0 such that each pair of clusters corresponding to an edge of H becomes $(2\varepsilon, \frac{d}{2})$ -super-regular, while each pair of clusters corresponding to an edge of R becomes $(2\varepsilon, d - \varepsilon)$ -regular.*

Proof. For each cluster $V \in V(R)$, let

$$A(V) = \left\{ x \in V : \begin{array}{l} |N_{G'}^+(x) \cap W| < (d - \varepsilon)m \text{ for some out-neighbour } W \text{ of } V \text{ in } H \\ \text{or } |N_{G'}^-(x) \cap W| < (d - \varepsilon)m \text{ for some in-neighbour } W \text{ of } V \text{ in } H \end{array} \right\}.$$

The definition of regularity implies that $|A(V)| \leq \Delta \varepsilon m$. Remove from each cluster V a set of size exactly $\Delta \varepsilon m$ containing $A(V)$. Since $\Delta \varepsilon \leq \frac{1}{2}$, it follows easily that all pairs corresponding to edges of R become $(2\varepsilon, d - \varepsilon)$ -regular. Moreover, the minimum degree of each pair corresponding to an edge of H is at least $(d - (\Delta + 1)\varepsilon)m \geq \frac{d}{2}m$, as required. \square

Next we note the easy fact that regular pairs have nearly perfect matchings and super-regular pairs have perfect matchings.

Lemma 12. *Suppose $\varepsilon > 0$ and $G = (A, B)$ is an $(\varepsilon, 2\varepsilon)$ -regular pair with $|A| = |B| = n$. Then G contains a matching of size at least $(1 - \varepsilon)n$. Furthermore, if G is $(\varepsilon, 2\varepsilon)$ -super-regular then G has a perfect matching.*

Proof. For the first statement we verify the conditions of the defect Hall theorem (Proposition 7) with $D = \varepsilon n$. We need to show that $|N(S)| \geq |S| - D$ for $S \subseteq A$. We can assume that $|S| \geq D = \varepsilon n$. Then by ε -regularity, all but at most εn vertices in B have at least $\varepsilon|S| > 0$ neighbours in S . Therefore $|N(S)| \geq (1 - \varepsilon)n \geq |S| - \varepsilon n$, as required. For the second statement we need to show that $|N(S)| \geq |S|$ for $S \subseteq A$. For any $x \in S$ we have $d(x) \geq 2\varepsilon n$ by super-regularity, so we can assume that $|S| \geq 2\varepsilon n$. Then as before we have $|N(S)| \geq (1 - \varepsilon)n$, so we can assume that $|S| > (1 - \varepsilon)n$. But we also have $d(y) \geq 2\varepsilon n$ for any $y \in B$, so $N(y) \cap S \neq \emptyset$, i.e. $N(S) = B$ and $|N(S)| = n \geq |S|$. \square

We will also need the following regularity criterion for finding a Hamilton cycle in a non-bipartite digraph. We say that a general digraph G on n vertices is ε -regular of density d if $\frac{e_G(X, Y)}{|X||Y|} = d \pm \varepsilon$ for all (not necessarily disjoint) subsets X, Y of $V(G)$ of size at least εn , and (ε, d) -super-regular if it is ε -regular and $\delta^\pm(G) \geq dn$.

Lemma 13. *Suppose $0 < \varepsilon \ll d \ll 1$, n is sufficiently large and G is an (ε, d) -super-regular digraph on n vertices. Then G is Hamiltonian.*

In fact, Frieze and Krivelevich [7, Theorem 4] proved that an (ε, d) -super-regular digraph has $(d - 4\varepsilon^{1/2})n$ edge-disjoint Hamilton cycles, which is a substantial strengthening of Lemma 13. Lemma 13 can also be deduced from Lemma 10 in [11].

Next we need a construction that we will use to preserve super-regularity of a pair when certain specified vertices are excluded.

Lemma 14. *Suppose $0 < \varepsilon \ll d \ll 1$, $G = (A, B)$ is an (ε, d) -super-regular pair with $|A| = |B| = n$ sufficiently large and $X \subseteq A$ with $|X| \leq n/3$. Then there is a set $Y \subseteq B$ with $|Y| = |X|$ such that $(A \setminus X, B \setminus Y)_G$ is $(2\varepsilon, d/2)$ -super-regular.*

Proof. If $|X| \leq 2\varepsilon n$ then we choose Y arbitrarily with $|Y| = |X|$. Next suppose that $|X| > 2\varepsilon n$. We let B_1 be the set of vertices in B that have less than $\frac{1}{2}d|A \setminus X|$ neighbours in $A \setminus X$. Then $|B_1| \leq \varepsilon n$ by ε -regularity of G . Consider choosing $B_2 \subseteq B \setminus B_1$ of size $|X| - |B_1|$ uniformly at random. For any x in A its degree in B_2 is $d_{B_2}(x) = |N_G(x) \cap B_2|$, which has hypergeometric distribution with parameters $(|B \setminus B_1|, d_{B \setminus B_1}(x), |B_2|)$. Super-regularity gives $\mathbb{E}[d_{B_2}(x)] = d_{B \setminus B_1}(x)|B_2|/|B \setminus B_1| > \varepsilon dn/2$, and the Chernoff bound (Proposition 9) applied with $a = n^{2/3}/\mathbb{E}d_{B_2}(x) > n^{-1/3}$ gives $\mathbb{P}(|d_{B_2}(x) - \mathbb{E}d_{B_2}(x)| > n^{2/3}) < 2e^{-an^{2/3}/3} < 2e^{-n^{1/3}/3}$. By a union bound, there is some choice of B_2 so that every x in A has $d_{B_2}(x) = d_{B \setminus B_1}(x)|B_2|/|B \setminus B_1| \pm n^{2/3} < 0.4d_B(x)$ (say). Let $Y = B_1 \cup B_2$. Then $(A \setminus X, B \setminus Y)_G$ is 2ε -regular, by ε -regularity of G . Furthermore, every $y \in B \setminus Y$ has $d_{A \setminus X}(y) \geq \frac{1}{2}d|A \setminus X|$ by definition of B_1 , and every x in $A \setminus X \subseteq A$ has $d_{B \setminus Y}(x) \geq d_B(x) - |B_1| - d_{B_2}(x) \geq \frac{1}{2}d|B \setminus Y|$. \square

Finally, given an (ε, d) -super-regular pair $G = (A, B)$, we will often need to isolate a small subpair that maintains super-regularity in any subpair that contains it. For $A^* \subseteq A$ and $B^* \subseteq B$ we say that (A^*, B^*) is an (ε^*, d^*) -ideal for (A, B) if for any $A^* \subseteq A' \subseteq A$ and $B^* \subseteq B' \subseteq B$ the pair (A', B') is (ε^*, d^*) -super-regular. The following lemma shows that ideals exist, and moreover randomly chosen sets A^* and B^* form an ideal with high probability.

Lemma 15. *Suppose $0 < \varepsilon \ll \theta, d < 1/2$, n is sufficiently large and $G = (A, B)$ is (ε, d) -super-regular with $n/2 \leq |A|, |B| \leq n$. Let $A^* \subseteq A$ and $B^* \subseteq B$ be independent uniformly random subsets of size θn . Then with high probability (A^*, B^*) is an $(\varepsilon/\theta, \theta d/4)$ -ideal for (A, B) .*

Proof. First we note that ε -regularity of G implies that (A', B') is ε/θ -regular for any $A' \subseteq A$ and $B' \subseteq B$ with $|A'|, |B'| \geq \theta n$. For each $x \in A$, the degree of x in B^* is $d_{B^*}(x) = |N_G(x) \cap B^*|$, which has hypergeometric distribution with parameters $(|B|, d_G(x), \theta n)$ and expectation $\mathbb{E}[d_{B^*}(x)] \geq \theta d_G(x)$. By super-regularity we have $d_G(x) \geq dn/2$, so by the Chernoff bound (Proposition 9) applied with $a = \theta dn/4 \mathbb{E}[d_{B^*}(x)] \geq d/4$, we have $\mathbb{P}(d_{B^*}(x) < \theta dn/4) < 2e^{-\theta d^2 n/48}$. By a union bound, there is some choice of B^* so that every $x \in A$ has at least $\theta dn/4$ neighbours in B^* , and so at least $(\theta d/4)|B'|$ neighbours in B' for any $B^* \subseteq B' \subseteq B$. Arguing similarly for A^* gives the result. \square

5. OVERVIEW OF THE PROOF

We will first prove a special case of Theorem 5. Although it would be possible to give a single argument that covers all cases, we believe it is instructive to understand the methods in a simplified setting before introducing additional complications. This section gives an overview of our techniques. We begin by defining additional constants such that

$$\frac{1}{n_0} \ll \varepsilon \ll d \ll \gamma \ll d' \ll \eta \ll \eta' \ll \beta \leq 1.$$

Note that this hierarchy of parameters will be used throughout the paper. By applying the Diregularity Lemma to G with parameters ε, d and $M' = 1/\varepsilon$, we obtain a reduced digraph $R_{G'}$ on k clusters of size m and an exceptional set V_0 . We will see that the degree sequences of $R_{G'}$ inherit many of the properties of the degree sequences of G . Then it will follow that $R_{G'}$ contains a union of cycles F which covers all but at most $O(d^{1/2}k)$ of the clusters of $R_{G'}$. We move the vertices of all clusters not covered by F into V_0 . By moving some further vertices into V_0 we can assume that all edges of F correspond to super-regular pairs.

Let $R_{G'}^*$ be the digraph obtained from $R_{G'}$ by adding the set V_0 of exceptional vertices and for each $x \in V_0$ and each $V \in R_{G'}$ adding the edge xV if x has an outneighbour in V and the edge Vx if x has an inneighbour in V . We would like to find a closed walk W in $R_{G'}^*$ such that

- (a) For each cycle C of F , W visits every cluster of C the same number of times, say m_C ;
- (b) We have $1 \leq m_C \leq m$, i.e. W visits every cluster at least once but not too many times;
- (c) W visits every vertex of V_0 exactly once;
- (d) For each $x_i \in V_0$ we can choose an inneighbour x_i^- in the cluster preceding x_i on W and an outneighbour x_i^+ in the cluster following x_i on W , so that as x_i ranges over V_0 all vertices x_i^+, x_i^- are distinct.

If we could find such a walk W then by properties (a) and (b) we can arrange that $m_C = m$ for each cycle C of F by going round C an extra $m - m_C$ times on one particular visit of W to C . Then we could apply properties (c) and (d) to choose inneighbours and outneighbours for every vertex of V_0 such that all choices are distinct. Finally, we could apply a powerful tool known as the Blow-up Lemma (see [14]) to find a Hamilton cycle C_{Ham} in G corresponding to W , where C_{Ham} has the property that whenever W visits a vertex of V_0 , C_{Ham} visits the same vertex, and whenever W visits a cluster V_i of $R_{G'}$, then C_{Ham} visits a vertex $x \in V_i$. (We will not discuss the Blow-up Lemma further, as in fact we will take a different approach that does not need it.)

To achieve property (a), we will build up W from certain ‘shifted’ walks, each of them satisfying property (a). Suppose R is a digraph, R' is a subdigraph of R , F is a 1-factor in R and a, b are vertices. A *shifted walk* (with respect to R' and F) from a to b is a walk $W(a, b)$ of the form

$$W(a, b) = X_1 C_1 X_1^- X_2 C_2 X_2^- \dots X_t C_t X_t^- X_{t+1},$$

where $X_1 = a$, $X_{t+1} = b$, C_i is the cycle of F containing X_i , and for each $1 \leq i \leq t$, X_i^- is the predecessor of X_i on C_i and the edge $X_i^- X_{i+1}$ belongs to R' . We say that $W(a, b)$ *traverses the cycles* C_1, \dots, C_t . Note that even if the cycles C_1, \dots, C_t are not distinct we say that W traverses t cycles. Note also that, for every cycle C of F , the walk $W(a, b) \setminus b$ visits the vertices of C an equal number of times.

Given a shifted walk $W = W(a, b)$ as above we say that W *uses* X if X appears in the list $\{X_1^-, \dots, X_t, X_t^-, X_{t+1}\}$. More generally, we say that X is *used* s *times* by W if it appears s times in the above list (counting multiplicities). Thus W uses $2t$ clusters, counting multiplicities. We say that W *internally uses* X if $X \in \{X_2, X_2^-, \dots, X_t, X_t^-\}$ (i.e. we do not count the uses of X_1^- or X_{t+1}). We also refer to the uses of X_2, \dots, X_{t+1} as *entrance uses* and X_1^-, \dots, X_t^- as *exit uses*. If X is used as both X_i and X_j for some $2 \leq i < j \leq t+1$ then we can obtain a shorter shifted walk from a to b by deleting the segment of W between X_i and X_j (retaining one of them). Similarly, we can obtain a shorter shifted walk if X is used as both X_i^- and X_j^- for some $1 \leq i < j \leq t$. Thus we can always choose shifted walks so that any cluster is used at most once as an entrance and at most once as an exit, and so is used at most twice in total.

We say that a cluster V is *entered* a *times* by W if W contains a edges whose final vertex is V and which do not lie in F (where the edges of W are counted with multiplicities). We have a similar definition for *exiting* V a *times*.

Next we define an auxiliary digraph H that plays a crucial role in our argument. Let $R_{G''}$ be the spanning subdigraph of $R_{G'}$ obtained by deleting all those edges corresponding to a pair of clusters whose density is less than d' . Let F be the 1-factor of $R_{G'}$ mentioned above. The vertices of H are the clusters of $R_{G''}$. We have an edge from a to b in H if there is a shifted walk with respect to $R_{G''}$ and F from a to b which traverses exactly one cycle. One can view H as a ‘shifted version’ of $R_{G''}$.

For now we will only consider the special case in which H is highly connected. Even then, the fact that the exceptional set V_0 can be much bigger than the cluster sizes creates a difficulty in ensuring property (b), that W does not visit a cluster too many times. A natural attempt to overcome this difficulty is the technique from [5]. In that paper we split each cluster V_i of $R_{G'}$ into two equal pieces V_i^1 and V_i^2 . If the splitting is done at random, then with high probability, the super-regularity between pairs of clusters corresponding to the edges of F is preserved. We then applied the Diregularity Lemma to the subdigraph of G induced by $V_0 \cup V_1^2 \cup \dots \cup V_k^2$ with parameters ε_2, d_2 and $M_2' = 1/\varepsilon_2$ to obtain a reduced graph R_2 and an exceptional set V_0^2 . The advantage gained is that by choosing $\varepsilon_2 \ll d_2 \ll \varepsilon$ the exceptional set V_0^2 becomes much smaller than the original cluster sizes and there is no difficulty with property (b) above. However, the catch is that in our present case the degrees are capped at $n/2$, and in the course of constructing the union of cycles in R_2 we would have to enlarge V_0^2 to such an extent that this approach breaks down.

Our solution is to replace condition (b) by the following property for W :

- (b') W visits every cluster of $R_{G'}$ at least once but does not *use* any cluster of $R_{G'}$ too many times.

This condition can be guaranteed by the high connectivity property of H . However, we now have to deal with the fact that W may ‘wind around’ each cycle of F too many times. This will be addressed by a shortcutting technique, where for each cycle C in F we consider the required uses of C en masse and reassign routes so as not to overload any part of C . A side-effect of this procedure is that we may obtain a union of cycles, rather than a single Hamilton cycle. However, using a judicious choice of W and a switching procedure for matchings, we will be able to arrange that these shortcuts do produce a single Hamilton cycle. In particular, this approach does not rely on the Blow-up Lemma.

6. STRUCTURE I: COVERING THE REDUCED DIGRAPH BY CYCLES

We start the proof by applying the Diregularity Lemma (Lemma 10) to G with parameters ε, d and $M' = 1/\varepsilon$, obtaining a reduced digraph $R_{G'}$ on k clusters of size m and an exceptional set V_0 . Initially we have $|V_0| \leq \varepsilon n$, although we will add vertices to V_0 during the argument. Note also that $n = km + |V_0|$.

6.1. Properties of $R_{G'}$. Our main aim in this section is to show that $R_{G'}$ contains an almost 1-factor F , more specifically, a disjoint union of directed cycles covering all but at most $7d^{1/2}k$ vertices of $R_{G'}$. To begin with, we show that the degree sequences of $R_{G'}$ have similar properties to the degree sequences of G .

Lemma 16.

- (i) $d_i^+(R_{G'}) \geq \frac{1}{m}d_{im}^+(G) - 2dk$;
- (ii) $d_i^-(R_{G'}) \geq \frac{1}{m}d_{im}^-(G) - 2dk$;
- (iii) $\delta^+(R_{G'}) \geq \frac{\beta}{2}k$;
- (iv) $\delta^-(R_{G'}) \geq \frac{\beta}{2}k$;
- (v) $d_i^+(R_{G'}) \geq \min \left\{ i + \frac{\beta}{2}k, \left(\frac{1}{2} - 2d\right)k \right\}$ or $d_{(1-\frac{\beta}{2})k-i}^-(R_{G'}) \geq k - i - 2dk$;
- (vi) $d_i^-(R_{G'}) \geq \min \left\{ i + \frac{\beta}{2}k, \left(\frac{1}{2} - 2d\right)k \right\}$ or $d_{(1-\frac{\beta}{2})k-i}^+(R_{G'}) \geq k - i - 2dk$.

Proof. We will only prove parts (i),(iii) and (v). Parts (ii), (iv) and (vi) can be obtained in exactly the same way as parts (i), (iii) and (v) respectively, by interchanging $+$ and $-$ signs. Consider i clusters with outdegrees at most $d_i^+(R_{G'})$ in $R_{G'}$. These clusters contain im vertices of G , so must include a vertex x of outdegree at least $d_{im}^+(G)$. Lemma 10 implies that the cluster V containing x satisfies

$$d_G^+(x) \leq d_{R_{G'}}^+(x) + (d + \varepsilon)n \leq d_{R_{G'}}^+(V)m + (d + \varepsilon)n + |V_0| \leq d_{R_{G'}}^+(V)m + \frac{3}{2}dn.$$

Therefore

$$d_i^+(R_{G'}) \geq d_{R_{G'}}^+(V) \geq \frac{1}{m}d_{im}^+(G) - \frac{3}{2}d\frac{n}{m} \geq \frac{1}{m}d_{im}^+(G) - 2dk,$$

which proves (i). Next, (iii) follows from (i), since $\delta^+(G) \geq \beta n$. To prove (v), suppose that $d_i^+(R_{G'}) < \min \left\{ i + \frac{\beta}{2}k, \left(\frac{1}{2} - 2d\right)k \right\}$. It follows from (i) that

$$d_{im}^+(G) < \min \{m(i + \beta k/2 + 2dk), mk/2\} \leq \min \{im + \beta n, n/2\}.$$

Using our degree assumptions gives $d_{n-im-\beta n}^-(G) \geq n - im$. Then by (ii) we have

$$d_{(1-\frac{\beta}{2})k-i}^-(R_{G'}) \geq \frac{1}{m}d_{(1-\frac{\beta}{2})km-im}^-(G) - 2dk \geq \frac{1}{m}d_{(1-\beta)n-im}^-(G) - 2dk \geq k - i - 2dk,$$

as required. \square

Unfortunately, $R_{G'}$ need not satisfy the hypothesis of Proposition 8, so we cannot use it to deduce the existence of a 1-factor in $R_{G'}$. The next lemma shows that a problem can only occur for subsets S of $V(R_{G'})$ of size close to $k/2$.

Lemma 17. *Let S be a subset of $V(R_{G'})$ such that either $|S| \leq (1/2 - 2d)k$ or $|S| > (1/2 + 2d)k$. Then $|N^+(S)|, |N^-(S)| \geq |S|$.*

Proof. Suppose firstly that $|S| \leq (1/2 - 2d)k$ but $|N^+(S)| < |S|$. By the minimum outdegree condition of $R_{G'}$ (Lemma 16 (iii)) we must have $|S| \geq \beta k/2$. Also $d_{|S|-2dk-1}^+(R_{G'}) \leq d_{|S|}^+(R_{G'}) < |S| \leq (1/2 - 2d)k$, so Lemma 16 (v) gives $d_{(1-\beta/2)k-|S|+2dk+1}^-(R_{G'}) \geq k - |S| + 1$. Thus there are at least $\beta k/2 + |S| - 2dk \geq |S|$ vertices of indegree at least $k - |S| + 1$. Now if x has indegree at least $k - |S| + 1$ then $N^-(x)$ intersects S , so x belongs to $N^+(S)$. We deduce that $|N^+(S)| \geq |S|$. A similar argument shows that $|N^-(S)| \geq |S|$ as well. Now suppose that

$|S| > (1/2 + 2d)k$ but $|N^+(S)| < |S|$, and consider $T = V(R_{G'}) \setminus N^+(S)$. Since $N^-(T) \cap S = \emptyset$, we have $|N^-(T)| < |T|$, and so $|T| > (1/2 - 2d)k$ by the first case. But now we can consider a subset T' of T of size $|T'| = (1/2 - 2d)k$ to see that $|N^-(T)| \geq |N^-(T')| \geq |T'| = (1/2 - 2d)k$, and so $|S| \leq (1/2 + 2d)k$, a contradiction. The claim for $|N^-(S)|$ follows by a similar argument. \square

Applying Hall's theorem as in Proposition 8, one can use Lemma 17 to partition the vertex set of $R_{G'}$ into a union of cycles and at most $4dk$ paths. However, for our approach we need to find a disjoint union of cycles covering almost all the vertices. The first step towards this goal will be to arrange that for each path its initial vertex has large indegree and its final vertex has large outdegree. To prepare the ground, we show in the next lemma that if $R_{G'}$ does not have a 1-factor, then it has many vertices of large outdegree and many vertices of large indegree.

Lemma 18. *If $R_{G'}$ does not have a 1-factor, then it contains more than $(1/2 + 2d)k$ vertices of outdegree at least $(1/2 - 2d)k$ and more than $(1/2 + 2d)k$ vertices of indegree at least $(1/2 - 2d)k$.*

Proof. Since $R_{G'}$ does not have a 1-factor, by Proposition 8 it contains a set S with $|N^+(S)| < |S|$. Then by Lemma 16 (i) we have

$$|S| > |N^+(S)| \geq d_{|S|}^+(R_{G'}) \geq \frac{1}{m} d_{m|S|}^+(G) - 2dk,$$

and so

$$d_{m|S| - \frac{\beta}{2}n}^+(G) \leq m(|S| + 2dk) \leq m|S| + \frac{\beta}{2}n.$$

Moreover, $(1/2 - 2d)k < |S| \leq (1/2 + 2d)k$ by Lemma 17. So if it were also the case that $d_{m|S| - \frac{\beta}{2}n}^+(G) < n/2 = \min\{m|S| + \beta n/2, n/2\}$, then $d_{(1-\beta/2)n - m|S|}^-(G) \geq (1 + \beta/2)n - m|S|$ and so by Lemma 16 (ii) we would have

$$d_{(1-\frac{\beta}{4})k - |S|}^-(R_{G'}) \geq \left(1 + \frac{\beta}{2}\right)k - |S| - 2dk \geq k - |S| + 1.$$

Then $R_{G'}$ contains at least $\beta k/4 + |S|$ vertices of indegree at least $k - |S| + 1$, and these must all belong to $N^+(S)$, a contradiction. It follows that $d_{m|S| - \frac{\beta}{2}n}^+(G) \geq n/2$. So Lemma 16 (i) gives

$$d_{|S| - \frac{\beta}{2}k}^+(R_{G'}) \geq d_{|S| - \frac{\beta}{2}\frac{n}{m}}^+(R_{G'}) \geq \frac{n}{2m} - 2dk \geq \left(\frac{1}{2} - 2d\right)k,$$

i.e. $R_{G'}$ contains at least $(1 + \beta/2)k - |S| \geq (1/2 + 2d)k$ vertices of outdegree at least $(1/2 - 2d)k$, which proves the first part of the lemma. The second part can be proved in exactly the same way. \square

Now we can show how to arrange the degree property for the paths.

Lemma 19. *The vertex set of $R_{G'}$ can be partitioned into a union of cycles and at most $4dk$ paths such that the initial vertices of the paths each have indegree at least $(1/2 - 2d)k$ and the final vertices of the paths each have outdegree at least $(1/2 - 2d)k$.*

Proof. We may assume that $R_{G'}$ does not have a 1-factor and so the consequences of Lemma 18 hold. We define an auxiliary digraph $R'_{G'}$ by adding $4dk$ new vertices v_1, v_2, \dots, v_{4dk} to $R_{G'}$, adding all possible edges between these vertices (in both directions), adding all edges of the form vv_i , where $1 \leq i \leq 4dk$ and v is a vertex of $R_{G'}$ of outdegree at least $(1/2 - 2d)k$ and finally adding all edges of the form $v_i v$ where $1 \leq i \leq 4dk$ and v is a vertex of $R_{G'}$ of indegree at least $(1/2 - 2d)k$. Then any vertex that previously had indegree at least $(1/2 - 2d)k$ now has indegree at least $(1/2 + 2d)k$, and similarly for outdegree. Also, Lemma 18 implies that every new vertex v_i has indegree and outdegree more than $(1/2 + 2d)k$. We claim that $R'_{G'}$ has a 1-factor. Having proved this, the result will follow by removing v_1, \dots, v_{4dk} from the cycles in the 1-factor. To prove the claim, let us take $S \subseteq V(R'_{G'})$. By Proposition 8 we need to show that $|N^+(S)| \geq |S|$. We consider cases according to the size of S . If $|S| \leq (1/2 - 2d)k$, then either $S \subseteq V(R_{G'})$, in which case $|N^+(S)| \geq |S|$ by Lemma 17, or S contains some new vertex v_i , in which case

$|N^+(S)| \geq d^+(v_i) \geq (1/2 + 2d)k \geq |S|$. Next suppose that $(1/2 - 2d)k < |S| \leq (1/2 + 2d)k$. As before, if S contains a new vertex v_i we have $|N^+(S)| \geq d^+(v_i) \geq (1/2 + 2d)k \geq |S|$, so we can assume $S \subseteq V(R_{G'})$. Now by Lemma 18 each new vertex v_i has at least $(1/2 + 2d)k > k - |S|$ inneighbours in $V(R_{G'})$ and so v_i has an inneighbour in S , i.e. $v_i \in N^+(S)$. Also, S has at least $(1/2 - 2d)k$ outneighbours in $R_{G'}$ by Lemma 17, so in $R'_{G'}$ we have $|N^+(S)| \geq 4dk + (1/2 - 2d)k \geq |S|$. Finally suppose that $|S| > (1/2 + 2d)k$. Let $T = V(R'_{G'}) \setminus N^+(S)$. Considering a subset $S' \subseteq S$ of size $(1/2 + 2d)k$ shows that $|T| \leq k - |N^+(S')| \leq k - |S'| = (1/2 - 2d)k$. However, $N^-(T)$ is disjoint from S , so if $|N^+(S)| < |S|$ we have $|T| > |N^-(T)|$. Now similar arguments to before give $|T| > (1/2 + 2d)k$, a contradiction. \square

6.2. The almost 1-factor. We now come to the main result of this section.

Lemma 20. $R_{G'}$ contains a disjoint union F of cycles covering all but at most $7d^{1/2}k$ of its vertices.

Proof. We implement the following algorithm. At each stage, the vertex set of $R_{G'}$ will be partitioned into some cycles and paths and a waste set W . In every path the initial vertex will have indegree at least $(1/2 - 2d)k$ and the final vertex will have outdegree at least $(1/2 - 2d)k$. One of the paths will be designated as the ‘active path’.

In the initial step, we begin with the partition guaranteed by Lemma 19. We have $W = \emptyset$ and choose an arbitrary path to be active.

In each iterative step we have some active path P . Let u be the initial vertex of P and v its final vertex. Let S be the sum of the numbers of vertices in all the paths. If at any point $S \leq 5d^{1/2}k$, then we move the vertices of all these paths into W and stop. Otherwise we define $\alpha = 5dk/S$ and for each path P_r , we let $\ell_r = \alpha|P_r|$. Note that the parameters S , α and $\{\ell_r\}$ are recalculated at each step. By our assumption on S we have $\alpha \leq d^{1/2}$. Also $\sum_r \ell_r = \alpha S = 5dk$.

For each cycle $C = w_1 \dots w_t w_1$ and $X \subseteq V(C)$ we write $X^+ = \{w_{i+1} : w_i \in X\}$ for the set of successors of vertices of X . For each path $P_r = w_1 \dots w_t$, $X \subseteq P_r$ and $1 \leq s \leq t$ we let $X^{+s} = \{w_j : \exists w_i \in X, i < j \leq i + s\}$. Also, for each path $P_r = w_1 \dots w_t$ which contains at least one outneighbour of v we let $i_r^v \geq 0$ be minimal such that $w_{i_r^v+1} \in N^+(v) \cap P_r$. Similarly, for each path $P_r = w_1 \dots w_t$ which contains at least one inneighbour of u we let $i_r^u \geq 0$ be minimal such that $w_{t-i_r^u} \in N^-(u) \cap P_r$. We claim that at least one of the following conditions holds:

- (1) There is a $w \in W$ such that $wu, vw \in E(R_{G'})$.
- (2) There is a cycle $C = w_1 \dots w_i w_{i+1} \dots w_t w_1$ such that $w_i u, v w_{i+1} \in E(R_{G'})$.
- (3) There is a path $P_r = w_1 \dots w_t$ and $1 \leq i < j \leq t$ with $j - i \leq \ell_r + 1$ such that $w_i u, v w_j \in E(R_{G'})$.
- (4) There is a path $P_r = w_1 \dots w_t$ with $i_r^u \leq \ell_r$ or $i_r^v \leq \ell_r$.

To see this, suppose to the contrary that all these conditions fail. Since (1) fails, then $(N^-(u) \cap W) \cap (N^+(v) \cap W) = \emptyset$ and so

$$\bullet |N^-(u) \cap W| + |N^+(v) \cap W| \leq |W|.$$

Since (2) fails, then for each cycle C we have $(N^-(u) \cap C)^+ \cap (N^+(v) \cap C) = \emptyset$ and so

$$\bullet |N^-(u) \cap C| + |N^+(v) \cap C| \leq |C| \text{ for each } C.$$

Since (4) fails then for each path P_r we have $|N^-(u) \cap P_r| \leq |P_r| - \ell_r$ and $|N^+(v) \cap P_r| \leq |P_r| - \ell_r$.

In particular

$$\bullet \text{ for each path } P_r, \text{ if } P_r \text{ does not meet both } N^-(u) \text{ and } N^+(v) \text{ then } |N^-(u) \cap P_r| + |N^+(v) \cap P_r| \leq |P_r| - \ell_r.$$

On the other hand if a path P_r meets both $N^-(u)$ and $N^+(v)$ then, since (3) fails we have $(N^-(u) \cap P_r)^{+(\ell_r+1)} \cap (N^+(v) \cap P_r) = \emptyset$. Moreover, since $i_r^u > \ell_r$ and since also (4) fails, we also have that $|(N^-(u) \cap P_r)^{+(\ell_r+1)}| \geq |N^-(u) \cap P_r| + \ell_r$. Altogether this gives that

$$\bullet \text{ for each path } P_r, \text{ if } P_r \text{ meets both } N^-(u) \text{ and } N^+(v) \text{ then } |N^-(u) \cap P_r| + |N^+(v) \cap P_r| \leq |P_r| - \ell_r.$$

Summing these inequalities gives

$$d^-(u) + d^+(v) \leq |W| + \sum_C |C| + \sum_r (|P_r| - \ell_r) = k - \sum_r \ell_r.$$

But we also have $\sum_r \ell_r = \alpha S = 5dk$ and $d^-(u), d^+(v) \geq (1/2 - 2d)k$ by the degree property of the paths. This contradiction shows that at least one of the conditions (1)–(4) holds.

According to the above conditions we take one of the following actions.

- (1) Suppose there is a $w \in W$ such that $wu, vw \in E(R_{G'})$. Then we replace the path P by the cycle $C = wuPvw$, replace W by $W \setminus \{w\}$, choose a new active path, and repeat.
- (2) Suppose there is a cycle $C = w_1 \dots w_i w_{i+1} \dots w_t w_1$ such that $w_i u, v w_{i+1} \in E(R_{G'})$. Then we replace the path P and the cycle C by the cycle $C' = w_1 \dots w_i u P v w_{i+1} \dots w_t w_1$, choose a new active path, and repeat.
- (3) Suppose there is a path $P_r = w_1 \dots w_t$ and $1 \leq i < j \leq t$ with $j - i \leq \ell_r + 1$ such that $w_i u, v w_j \in E(R_{G'})$.
 - (i) If $P_r \neq P$ then we replace the paths P and P_r with the path $P'_r = w_1 \dots w_i u P v w_j \dots w_t$, replace W with $W \cup \{w_{i+1}, \dots, w_{j-1}\}$, make P'_r the new active path, and repeat.
 - (ii) If $P_r = P$ (so $w_1 = u$ and $w_t = v$) then we replace P with the cycles $C_u = u w_2 \dots w_{i-1} w_i u$ and $C_v = v w_j \dots w_{t-1} v$, replace W with $W \cup \{w_{i+1}, \dots, w_{j-1}\}$, choose a new active path, and repeat.
- (4) Suppose there is a path $P_r = w_1 \dots w_t$ with $i_r^u \leq \ell_r$ or $i_r^v \leq \ell_r$.
 - (i) If $P_r \neq P$ and $i_r^u \leq \ell_r$ then we replace the paths P and P_r with the path $P'_r = w_1 \dots w_{t-i_r^u} u P v$, replace W with $W \cup \{w_{t-i_r^u+1}, \dots, w_t\}$, make P'_r the new active path, and repeat.
 - (ii) If $P_r \neq P$ and $i_r^v \leq \ell_r$ then we replace the paths P and P_r with the path $P'_r = u P v w_{i_r^v+1} \dots w_t$, replace W with $W \cup \{w_1, \dots, w_{i_r^v}\}$, make P'_r the new active path, and repeat.
 - (iii) If $P_r = P$ (so $w_1 = u$ and $w_t = v$) and $i_r^u \leq \ell_r$ then we replace P with the cycle $C = u P w_{t-i_r^u} u$, replace W with $W \cup \{w_{t-i_r^u+1}, \dots, w_t\}$, choose a new active path, and repeat.
 - (iv) If $P_r = P$ and $i_r^v \leq \ell_r$ then we replace P with the cycle $C = v w_{i_r^v+1} P v$, replace W with $W \cup \{w_1, \dots, w_{i_r^v}\}$, choose a new active path, and repeat.

At each step the number of paths is reduced by at least 1, so the algorithm will terminate. It remains to show that $|W| \leq 7d^{1/2}k$. Recall that at every step we have $\ell_r = \alpha|P_r| \leq d^{1/2}|P_r|$ for each path P_r . For every vertex w added to W we charge its contribution to the path that w initially belonged to. To calculate the total contribution we break it down by the above cases and by initial paths. Cases (1) and (2) do not increase the size of W . In Case 3(i), every initial path P_r is merged with an active path P at most once, and then its remaining vertices stay in the active path until a new active path is chosen, so this gives a contribution to W of at most $\ell_r \leq d^{1/2}|P_r|$ from P_r . In Case 3(ii), the vertices of the active path $P_r = P$ are contained in a union $\cup_{i \in I} V(P_i)$ of some subset of the initial paths (excluding some vertices already moved into W). These paths collectively contribute at most $\alpha|P| \leq d^{1/2} \sum_{i \in I} |P_i|$, and each initial path is merged at most once into such a path P . In Cases 4(i) and 4(ii), as in Case 3(i), an initial path P_r contributes at most $\alpha|P_r|$. In Cases 4(iii) and 4(iv), as in Case 3(ii), the vertices of the active path $P_r = P$ are contained in a union $\cup_{i \in I} V(P_i)$ of some subset of the initial paths and contribute at most $\alpha|P| \leq d^{1/2} \sum_{i \in I} |P_i|$. So each initial path contributes to W at most twice: once when it is merged into the active path (in Cases 3(i), 4(i) or 4(ii)) and once when this active path is turned into one or two cycles (in Cases 3(ii), 4(iii) or 4(iv)). Therefore we get a total contribution from the paths of at most $2d^{1/2}k$ to W . Finally, there is another contribution of at most $5d^{1/2}k$ if at any step we have $S \leq 5d^{1/2}k$. In total we have $|W| \leq 7d^{1/2}k$. \square

6.3. Further properties of F . Now we have an almost 1-factor F in $R_{G'}$, i.e. a disjoint union of cycles covering all but at most $7d^{1/2}k$ clusters of $R_{G'}$. We move all vertices of these uncovered

clusters into V_0 , which now has size at most $8d^{1/2}n$. During the proof of Theorem 5 it will be helpful to arrange that each cycle of F has length at least 4 (say) and moreover, all pairs of clusters corresponding to edges of F correspond to super-regular pairs. (This assumption on the lengths is not actually necessary but does make some of the arguments in the final section more transparent.)

We will now show that we may assume this. Indeed, if F contains cycles of lengths less than 4, we arbitrarily partition each cluster of $R_{G'}$ into 2 parts of equal size. (If the sizes of the clusters are not divisible by 2, then before the partitioning we move at most 1 vertex from each cluster into V_0 in order to achieve this.) Consider the digraph $R'_{G'}$ whose vertices correspond to the parts and where two vertices are joined by an edge if the corresponding bipartite subdigraph of G' is $(2\varepsilon, \frac{2d}{3})$ -regular. It is easy to check that this digraph contains the 2-fold ‘blowup’ of $R_{G'}$, i.e. each original vertex is replaced by an independent set of 2 new vertices and there is an edge from a new vertex x to a new vertex y if there was such an edge between the original vertices. Each cycle of length ℓ of F induces an 2-fold blowup of C_ℓ in $R'_{G'}$, which contains a cycle of length $2\ell \geq 4$. So $R'_{G'}$ contains a 1-factor F' all of whose cycles have length at least 4. Note that the size of V_0 is now at most $9d^{1/2}n$.

Secondly, we apply Lemma 11 to make the pairs of clusters corresponding to edges of F' $(4\varepsilon, \frac{d}{3})$ -super-regular by moving exactly $4\varepsilon|V_i|$ vertices from each cluster V_i into V_0 and thus increasing the size of V_0 to at most $10d^{1/2}n$. For convenience, having made these alterations, we will still denote the reduced digraph by $R_{G'}$, the order of $R_{G'}$ by k , its vertices (the clusters) by V_1, \dots, V_k and their sizes by m . We also rename F' as F . We sometimes refer to the cycles in F as F -cycles.

6.4. A modified reduced digraph. Let $R_{G''}$ be the spanning subdigraph obtained from $R_{G'}$ by deleting all those edges which correspond to pairs of density at most d' . Recalling that $d \ll d'$, we note that the density of pairs corresponding to edges in $R_{G''}$ is much larger than the proportion $10\sqrt{d}$ of vertices lying in V_0 . The purpose of $R_{G'}$ was to construct F so that this property would hold. Now we have no further use for $R_{G'}$ and will work only with $R_{G''}$. (Actually, we could use either $R_{G''}$ or $R_{G'}$ for the special case in the next section, but we need to work with $R_{G''}$ in general.)

Let G'' be the digraph obtained from G' obtained by deleting all edges belonging to pairs (X, Y) of clusters so that $(X, Y)_{G''}$ has density at most d' . We say that a vertex $x \in X$ is *typical* if

- $d_{G''}^\pm(x) \geq d_G^\pm(x) - 4d'n$;
- there are at most $\sqrt{\varepsilon}k$ clusters Y such that x does not have $(1 \pm 1/2)d_{XY}m$ outneighbours in Y , where d_{XY} denotes the density of the pair $(X, Y)_{G''}$. The analogous statement also holds for the inneighbourhood of x .

Lemma 21. *By moving exactly $16\sqrt{\varepsilon}m$ vertices from each cluster into V_0 , we can arrange that each vertex in each cluster of $R_{G''}$ is typical. We still denote the cluster sizes by m . Then we have*

- (i) $d_i^+(R_{G''}) \geq \frac{1}{m}d_{im}^+(G) - 5d'k$;
- (ii) $d_i^-(R_{G''}) \geq \frac{1}{m}d_{im}^-(G) - 5d'k$;
- (iii) $\delta^+(R_{G''}) \geq \frac{\beta}{2}k$;
- (iv) $\delta^-(R_{G''}) \geq \frac{\beta}{2}k$;
- (v) $d_i^+(R_{G''}) \geq \min \left\{ i + \frac{\beta}{2}k, \left(\frac{1}{2} - 5d' \right) k \right\}$ or $d_{(1-\frac{\beta}{2})k-i}^-(R_{G''}) \geq k - i - 5d'k$;
- (vi) $d_i^-(R_{G''}) \geq \min \left\{ i + \frac{\beta}{2}k, \left(\frac{1}{2} - 5d' \right) k \right\}$ or $d_{(1-\frac{\beta}{2})k-i}^+(R_{G''}) \geq k - i - 5d'k$.

Proof. Suppose that we are given clusters X, Y such that XY is an edge of $R_{G'}$. Write d_{XY} for the density of $(X, Y)_{G'}$. We say that $x \in X$ is *out-typical* for Y if (in G') x has $(1 \pm 1/3)d_{XY}m$ outneighbours in Y . Since the pair $(X, Y)_{G'}$ is 4ε -regular, it follows that at most $8\varepsilon m$ vertices

of X are not out-typical for Y . Then on average, a vertex of X is not out-typical for at most $8\epsilon k$ clusters. It follows that there are at most $8\sqrt{\epsilon}m$ vertices x in X for which there are more than $\sqrt{\epsilon}k$ clusters Y such that x is not out-typical for Y . Therefore we can remove a set of exactly $8\sqrt{\epsilon}m$ vertices from each cluster so that all of the remaining vertices are out-typical for at least $(1 - \sqrt{\epsilon})k$ clusters. We proceed similarly for the neighbourhood of each cluster. Altogether, we have removed exactly $16\sqrt{\epsilon}m$ vertices from each cluster. These vertices are added to V_0 , which now has size $|V_0| \leq 11\sqrt{dn}$. Now consider some cluster X and a vertex $x \in X$. Since x is out-typical for all but at most $\sqrt{\epsilon}k$ clusters, it sends at most $\sqrt{\epsilon}k \cdot m + k \cdot 2d'm \leq 3d'n$ edges into clusters Y such that $(X, Y)_{G'}$ has density at most d' . Then the following estimate shows that x is typical:

$$d_{G''}(x) \geq d_{G'}(x) - 3d'n - |V_0| \geq d_G(x) - (d + \epsilon)n - 3d'n - 11\sqrt{dn} \geq d_G(x) - 4d'n.$$

For (i)–(vi), we proceed similarly as in the proof of Lemma 16. For (i), consider i clusters with outdegrees at most $d_i^+(R_{G''})$ in $R_{G''}$. These clusters contain im vertices of G , so must include a typical vertex x of outdegree at least $d_{im}^+(G)$. As in the previous estimate, the cluster V containing x satisfies

$$d_{im}^+(G) \leq d_G^+(x) \leq d_{R_{G''}}^+(V)m + 4d'n + |V_0| \leq d_{R_{G''}}^+(V)m + \frac{9}{2}d'n.$$

Therefore

$$d_i^+(R_{G''}) \geq d_{R_{G''}}^+(V) \geq \frac{1}{m}d_{im}^+(G) - \frac{9}{2}d'\frac{n}{m} \geq \frac{1}{m}d_{im}^+(G) - 5d'k,$$

which proves (i). Next, (iii) follows from (i), since $\delta^+(G) \geq \beta n$. The proof of (v) is the same as that of (v) in Lemma 16, with $2d$ replaced by $5d'$. The proofs of the other three assertions are similar. \square

By removing at most one extra vertex from each cluster we may assume that the size of each cluster is even. We continue to denote the sizes of the modified clusters by m and the set of exceptional vertices by V_0 . The large-scale structure of our decomposition will not undergo any significant further changes: there will be no further changes to the cluster sizes, although in some subsequent cases we may add a small number of clusters to V_0 in their entirety. For future reference we note the following properties:

- $|V_0| \leq 11\sqrt{dn}$,
- all edges of $R_{G''}$ correspond to $(10\epsilon, d'/2)$ -regular pairs (the deletion of atypical vertices may have reduced the densities slightly),
- all edges of F correspond to $(10\epsilon, d/4)$ -super-regular pairs.

7. THE HIGHLY CONNECTED CASE

In this section we illustrate our methods by proving Theorem 5 in the case when the auxiliary graph H is strongly ηk -connected. We recall that $d' \ll \eta \ll \beta$, and that H was defined in Section 5 as a ‘shifted version’ of $R_{G''}$, i.e. there is an edge in H from a cluster V_i to a cluster V_j if there is a shifted walk (with respect to $R_{G''}$ and F) from V_i to V_j which traverses exactly one cycle. We refer to that section for the definitions of when a cluster is ‘used’ or ‘internally used’ by a shifted walk, and recall that we can assume that any cluster is used at most once as an entrance and at most once as an exit.

Lemma 22. *Suppose H is strongly ck -connected for some $c > 0$ and a, b are vertices of H (i.e. clusters). Then there is a collection of at least $c^2k/16$ shifted walks (with respect to $R_{G''}$ and F) from a to b such that each walk traverses at most $2/c$ cycles and each cluster is internally used by at most one of the walks.*

Proof. Since H is strongly ck -connected we can find ck internally disjoint paths P_1, \dots, P_{ck} from a to b . There cannot be $ck/2$ of these paths each having at least $2/c$ internal vertices, as H has k vertices. Therefore H contains at least $\ell := ck/2$ internally disjoint paths P_1, \dots, P_ℓ

(say, after relabelling) from a to b which have length at most $2/c$. Note that each of these corresponds to a shifted walk from a to b which traverses at most $2/c$ cycles. Let W_1, \dots, W_ℓ denote these shifted walks. Since the P_i are internally disjoint, each cluster x is internally used by at most 2 of the shifted walks W_j (either as an entrance or as an exit). Each shifted walk W_i internally uses at most $4/c$ clusters, so there are at most $8/c - 1$ other shifted walks W_j which internally use a cluster that W_i also uses internally. Thus we can greedily choose a subset of the walks W_1, \dots, W_ℓ having the required properties. \square

Given any cluster X , recall that we write X^+ for the successor of X on F and X^- for its predecessor. For every X , we apply Lemma 15 with $\theta = 16d$ to the $(10\varepsilon, d/4)$ -super-regular pair $(X, X^+)_{G'}$ to obtain an $(\sqrt{\varepsilon}, d^2)$ -ideal (X_1, X_2^+) . Set $X^* := X_1 \cup X_2$ (where (X_1^-, X_2) is the ideal chosen for (X^-, X)). Then, by Lemma 15, we have $|X^*| \leq 32dm$ and for any $X^* \subseteq X' \subseteq X$ and $(X^+)^* \subseteq (X^+)' \subseteq X^+$ the pair $(X', (X^+)')$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular.

First we construct the walk W described in the overview. List the elements of the exceptional set as $V_0 = \{x_1, \dots, x_r\}$. We go through the list sequentially, and for each x_i we pick clusters X_i and Y_i of $R_{G'}$ and vertices $x_i^- \in N_G^-(x_i) \cap (X_i \setminus X_i^*)$ and $x_i^+ \in N_G^+(x_i) \cap (Y_i \setminus Y_i^*)$ such that $x_1^-, x_1^+, \dots, x_r^-, x_r^+$ are distinct and moreover no cluster of $R_{G''}$ appears more than $m/60$ times as a cluster of the form X_i, Y_i (and thus no cluster appears more than $m/20$ times as a cluster of the form X_i, X_i^+, Y_i, Y_i^-). To see that this is possible, recall that $|V_0| \leq 11d^{1/2}n$ and $|X^*| \leq 32dm$ for all X . At most $3|V_0|$ vertices belong to V_0 or to the set $\{x_1^-, x_1^+, \dots, x_{i-1}^-, x_{i-1}^+\}$, and at most $120|V_0|$ belong to clusters that appear at least $m/60$ times as X_j or Y_j for x_j with $j < i$. Therefore at most $1500d^{1/2}n \leq \beta n \leq \delta^\pm(G)$ vertices are unavailable at stage i , so we can choose x_i^- and X_i as required. A similar argument applies for x_i^+ and Y_i . Note that by construction each cluster contains at most $m/20$ of the vertices x_i^\pm .

Next we sequentially define shifted walks $W(Y_i, X_{i+1}^+)$ with respect to $R_{G''}$ and F from Y_i to X_{i+1}^+ for $1 \leq i \leq r-1$. We want each $W(Y_i, X_{i+1}^+)$ to traverse at most $2/\eta$ cycles and each cluster to be internally used at most $m/30$ times by the collection of all the walks $W(Y_i, X_{i+1}^+)$. To see that this is possible, suppose we are about to find $W(Y_i, X_{i+1}^+)$ and let A be the set of clusters internally used at least $m/40$ times by the walks $W(Y_j, X_{j+1}^+)$ with $j < i$. Since each of our walks internally uses at most $4/\eta$ clusters (although it visits many more) we have $|A| < \frac{11d^{1/2}n \cdot 4/\eta}{m/40} < \eta^2 k/16$ (since $d \ll \eta$). Now Lemma 22 implies that we can find a shifted walk $W(Y_i, X_{i+1}^+)$ from Y_i to X_{i+1}^+ that traverses at most $2/\eta$ cycles and does not internally use any cluster in A . We may assume that $W(Y_i, X_{i+1}^+)$ uses each cluster at most once as an entrance and at most once as an exit, and then no cluster is internally used more than $2 + m/40 \leq m/30$ times by the collection of all the walks $W(Y_j, X_{j+1}^+)$ for all $j \leq i$, as required.

We conclude this step by choosing a shifted walk $W(Y_r, X_1^+)$ from Y_r to X_1^+ . Since there may be clusters in $R_{G''}$ that we have not yet used, we construct this walk as a sequence of at most k shifted walks each traversing at most $2/\eta$ cycles, in such a way that every cluster is used at least once by $W(Y_r, X_1^+)$.

This leads us to define a closed walk W with vertex set $V_0 \cup V(R_{G''})$ as follows. Let $W(Y_i, X_{i+1})$ be the walk from Y_i to X_{i+1} which is obtained from $W(Y_i, X_{i+1}^+)$ by adding the path from X_{i+1}^+ to X_{i+1} in F . We now define

$$W = x_1 W(Y_1, X_2) x_2 \dots x_r W(Y_r, X_1) x_1.$$

Using the choice of the clusters X_i and Y_i it is easy to see that W uses every cluster of $R_{G''}$ at most $m/20 + m/30 + k \cdot 8/\eta \leq m/10$ times. Thus W has the properties mentioned in the overview, namely:

- (a) For each cycle C of F , W visits every vertex of C the same number of times;
- (b') W visits every cluster of $R_{G''}$ at least once and uses every cluster of $R_{G''}$ at most $m/10$ times;
- (c) W visits every vertex of V_0 exactly once;

- (d) For each $x_i \in V_0$ we have chosen an inneighbour x_i^- in the cluster X_i preceding x_i on W and an outneighbour x_i^+ in the cluster Y_i following x_i on W , so that as x_i ranges over V_0 all the vertices x_i^+ , x_i^- are distinct.

Now we fix edges in G corresponding to all edges of W that do not lie within a cycle of F . We have already fixed the edges incident to vertices of V_0 (properties (c) and (d)). Then we note that the remaining edges of W not in $E(F)$ are precisely those of the form AB where A is used as an exit by W and B is used as an entrance by W . To see this, note that we cannot have $A = B^-$, as then B would be used twice as an entrance in one of the shifted walks constructed above, which is contrary to our assumption. Next we proceed through the clusters V_1, \dots, V_k sequentially choosing edges as follows. When we come to V_i , we consider each $j < i$ in turn. If $V_i V_j \notin E(F)$ we let w_{ij} be the number of times that W uses $V_i V_j$. Similarly, if $V_j V_i \notin E(F)$ we let w_{ji} be the number of times that W uses $V_j V_i$. We aim to choose a matching in G that avoids all previously chosen vertices and uses w_{ij} edges from $V_i \setminus V_i^*$ to $V_j \setminus V_j^*$ and w_{ji} edges from $V_j \setminus V_j^*$ to $V_i \setminus V_i^*$. This can be achieved greedily as follows. Suppose for example that $w_{ij} > 0$ and that when we come to V_j the available vertices are $V_i' \subseteq V_i$ and $V_j' \subseteq V_j$. Since every cluster is used at most $m/10$ times we have $w_{ij} \leq m/10$, and we have $|V_i'|, |V_j'| \geq m/2$ (say, taking account of at most $m/10$ uses, $m/20$ vertices x_i^\pm and $32dm$ vertices in V_i^* or V_j^*). Then $(V_i', V_j')_{G''}$ induces a $(20\varepsilon, d'/3)$ -regular pair, so by Lemma 12 has a matching of size at least $(1 - 20\varepsilon)m/2 > w_{ij}$. The same argument can be used if we also have $w_{ji} > 0$. After considering all such pairs (i, j) we have found edges in G corresponding to all edges of W that do not lie within a cycle of F .

Now let Entry denote the set of all those vertices which do not lie in the exceptional set and which are the final vertex of an edge of G that we have fixed (i.e. the edges incident to the vertices in V_0 and the edges chosen in the previous paragraph). Similarly, let Exit denote the set of all those vertices which do not lie in the exceptional set and which are the initial vertex of an edge of G that we have fixed. Note that $\text{Entry} \cap \text{Exit} = \emptyset$.

For every cluster U , let $U_{\text{Exit}} := U \cap \text{Exit}$ and $U_{\text{Entry}} = U \cap \text{Entry}$. Since W was built up by shifted walks, it follows that $|U_{\text{Exit}}| = |U_{\text{Entry}}^+|$. Moreover, since we chose Entry and Exit to avoid U^* , we know that $(U \setminus U_{\text{Exit}}, U^+ \setminus U_{\text{Entry}}^+)_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular, so contains a perfect matching by Lemma 12. Now the edges of these perfect matchings together with the edges of W that we fixed in the previous step form a 1-factor \mathcal{C} of G . It remains to modify \mathcal{C} into a Hamilton cycle of G .

The following statement provides us with the tool we need. For any cluster U , let $G_U := (U^- \setminus U_{\text{Exit}}^-, U \setminus U_{\text{Entry}})_{G'}$ and let Old_U be the perfect matching in G_U which is contained in \mathcal{C} .

For any cluster U , we can find a perfect matching New_U in G_U so that if we replace Old_U in \mathcal{C} with New_U , then all vertices of G_U will lie on a common cycle in the new 1-factor \mathcal{C} . In particular, all vertices in $U \setminus U_{\text{Entry}}$ will lie on a common cycle C_U in \mathcal{C} (†) and moreover any pair of vertices of G that were formerly on a common cycle are still on a common cycle after we replace Old_U by New_U .

To prove this statement we proceed as follows. For every $u \in U \setminus U_{\text{Entry}}$, we move along the cycle C_u of \mathcal{C} containing u (starting at u) and let $f(u)$ be the first vertex on C_u in $U^- \setminus U_{\text{Exit}}^-$. Define an auxiliary digraph J on $U \setminus U_{\text{Entry}}$ such that $N_J^+(u) := N_{G_U}^+(f(u))$. So J is obtained by identifying each pair $(u, f(u))$ into one vertex with an edge from $(u, f(u))$ to $(v, f(v))$ if G_U has an edge from $f(u)$ to v . Now G_U is $(\sqrt{\varepsilon}, d^2)$ -super-regular by the definition of the sets U^* , so J is also $(\sqrt{\varepsilon}, d^2)$ -super-regular (according to the definition for non-bipartite digraphs). By Lemma 13, J has a Hamilton cycle, which clearly corresponds to a perfect matching New_U in G' with the desired property.

Now we apply (†) to every cluster U sequentially. We continue to denote the resulting 1-factor by \mathcal{C} and we write C_U for the cycle that now contains all vertices in $U \setminus U_{\text{Entry}}$. Since U_{Entry}

and U_{Exit} have size at most $m/4$ (say) for any U , we have $V(G_U) \cap V(G_{U^+}) \neq \emptyset$, so $C_U = C_{U^+}$. Then $C_{U^-} = C_U = C_{U^+}$, and since $U_{Entry} \cap U_{Exit} = \emptyset$, we deduce that C_U actually contains all vertices of U . Then $C_U = C_{U^+}$ implies that C_U contains all vertices lying in clusters belonging to the cycle of F containing U .

We now claim that \mathcal{C} is in fact a Hamilton cycle. For this, recall that $W(Y_r, X_1^+)$ used every cluster. Write $W(Y_r, X_1^+) = U_1 C_1 U_1^- U_2 C_2 U_2^- \dots U_t C_t U_t^- U_{t+1}$, where each cluster appears at least once in U_1, \dots, U_{t+1} . Let $u_i^- u_{i+1}$ be the edge that we have chosen for the edge $U_i^- U_{i+1}$ on $W(Y_r, X_1^+)$. Note that for each $i = 1, \dots, t$ the vertices u_{i+1} and u_i^- lie on a common cycle of \mathcal{C} , as this holds by construction of \mathcal{C} , whatever matchings we use to create \mathcal{C} . Since $u_i, u_i^- \in U_i$ also lie on a common cycle, this means that all of u_1, \dots, u_t (and thus also u_{t+1}) lie on the same cycle C of \mathcal{C} , which completes the proof.

8. STRUCTURE II: SHIFTED COMPONENTS, TRANSITIONS AND THE EXCEPTIONAL SET

Having illustrated our techniques in the case when H is strongly ηk -connected, we now turn to the case when this does not hold. In this section we impose further structure on G by introducing ‘shifted components’ of H and various matchings linking these components and the vertices of the exceptional set V_0 . In the first subsection we construct the shifted components. We describe some of their properties in the second subsection. The third subsection describes a process by which our shifted walk W will make transitions between the shifted components. In the fourth subsection we partition V_0 into 4 parts according to the existence of certain matchings between V_0 and the remainder of the digraph. Then we complete the description of the transitions in the fifth subsection. Since we need to introduce a large amount of notation in this section, we conclude with a summary of the important points.

We recall that $\varepsilon \ll d \ll \gamma \ll d' \ll \eta \ll \eta' \ll \beta$ and $|V_0| \leq 11d^{1/2}n$.

8.1. Shifted components of H . Note that the in- and outdegrees of H are obtained by permuting those of $R_{G''}$, so H has the same in- and outdegree sequences as $R_{G''}$, and the bounds in Lemma 21 also apply to H . We start by establishing an expansion property for subsets of $V(H)$.

Lemma 23. *If $X \subseteq V(H)$ with $|X| \leq (1 - \beta)k/2$ then*

$$|N_H^\pm(X)| \geq |X| + \frac{\beta}{2}k - 5d'k - 1 \geq |X| + \frac{\beta}{4}k.$$

Proof. The argument is similar to that for Lemma 17. By symmetry it suffices to obtain the bound for $|N_H^+(X)|$. Suppose for a contradiction that $|N_H^+(X)| < |X| + \frac{\beta}{2}k - 5d'k - 1$. By Lemma 21(iii) we have $|X| > 5d'k + 1$. Also $d_{|X| - 5d'k - 1}^+(H) \leq |N_H^+(X)| < (1/2 - 5d')k$, so by Lemma 21(v) we have $d_{(1-\beta/2)k - |X| + 5d'k + 1}^-(H) \geq k - |X| + 1$. Then H contains at least $|X| + \beta k/2 - 5d'k$ vertices of indegree at least $k - |X| + 1$, and these all belong to $N_H^+(X)$, a contradiction. \square

We are assuming that H is not strongly ηk -connected, so we can choose a separator S of H of size $|S| < \eta k$. Thus we have a partition of the vertices of H into sets S , C , and D such that $H \setminus S$ does not contain an edge from C to D (although it might contain edges from D to C).

Lemma 24. $|C|, |D| = k/2 \pm 2\eta k$.

Proof. Suppose for a contradiction that $|D| < k/2 - 2\eta k$. If the stronger inequality $|D| \leq (1 - \beta)k/2$ holds then Lemma 23 implies that $|N_H^-(D)| \geq |D| + \frac{\beta}{4}k > |D| + |S|$, a contradiction. So we may assume that $|D| \geq (1 - \beta)k/2$. Let D' be a subset of D of size $(1 - \beta)k/2$. Now the first inequality of Lemma 23 implies that

$$|N_H^-(D)| \geq |N_H^-(D')| \geq k/2 - 5d'k - 1 > (|D| + 2\eta k) - 5d'k - 1 > |D| + \eta k \geq |D| + |S|,$$

a contradiction. The bound $|C| \geq k/2 - 2\eta k$ is obtained in a similar way, which proves the lemma. \square

Let C_{small} be the set of vertices in C which (in the digraph H) have at most $\beta k/10$ inneighbours in C . Let D_{small} be the set of vertices in D which (in the digraph H) have at most $\beta k/10$ outneighbours in D .

Lemma 25. $|C_{\text{small}}|, |D_{\text{small}}| \leq 8\eta k$.

Proof. Let C_{big} be the set of vertices in C which have at least $k/2 - \eta k$ outneighbours in H . We claim that $|C_{\text{big}}| \geq \beta k/5$. To see this, first note that Lemma 24 and the fact that there are no edges from C to D imply that D contains no vertex of indegree greater than $|D| + |S| \leq k/2 + 3\eta k$. So again by Lemma 24, the number of vertices of indegree greater than $k/2 + 3\eta k$ in H is at most $k/2 + 3\eta k$, which gives $d_{k/2-3\eta k}^- \leq k/2 + 3\eta k$. Now Lemma 21(v) with $i = k/2 - \beta k/4$ says that $d_{k/2-\beta k/4}^+ \geq (1/2 - 5d')k$ or $d_{k/2-\beta k/4}^- \geq k/2 + \beta k/4 - 5d'k$. The latter option cannot hold, as it would contradict our previous inequality for $d_{k/2-3\eta k}^-$, so the former option holds, and H has at least $k/2 + \beta k/4$ vertices of outdegree at least $k/2 - 5d'k \geq k/2 - \eta k$. By Lemma 24, C has to contain at least $\beta k/5$ of these vertices of high outdegree, which proves the claim.

Now note that yet another application of Lemma 24 shows that every vertex in C_{big} has at least $k/2 - \eta k - |S| \geq |C| - 4\eta k$ outneighbours in $H[C]$. Suppose that $|C_{\text{small}}| > 8\eta k$. Then every vertex in C_{big} has more than half of the vertices of C_{small} as outneighbours. This in turn implies that there is a vertex in C_{small} with more than half the vertices in C_{big} as inneighbours. In particular, it has more than $\beta k/10$ inneighbours in C . This contradicts the definition of C_{small} , so in fact $|C_{\text{small}}| \leq 8\eta k$. The argument for D_{small} is similar. \square

Let $C' := C \setminus C_{\text{small}}$ and $D' := D \setminus D_{\text{small}}$.

Lemma 26. $H[C']$ and $H[D']$ are strongly $\eta'k$ -connected.

Proof. By symmetry it suffices to consider $H[C']$. The definition of C_{small} and Lemma 25 give $\delta^-(H[C']) \geq \beta k/10 - |C_{\text{small}}| \geq \beta k/11$. Suppose that $H[C']$ is not strongly $\eta'k$ -connected. Then there is a separator T of size at most $\eta'k$ and a partition U, W of $C' \setminus T$ such that $H[C'] \setminus T$ contains no edge from U to W . Note that $|W| \geq \delta^-(H[C']) - |T| \geq \beta k/12$. So

$$|U| \leq |C'| - |W| \leq (k/2 + 2\eta k) - \beta k/12 \leq k/2 - \beta k/13. \quad (1)$$

If the stronger inequality $|U| \leq (1 - \beta)k/2$ holds then Lemma 23 implies that $|N^+(U)| \geq |U| + \beta k/4 > |U| + |S| + |T| + |C_{\text{small}}|$, a contradiction. So we may assume that $|U| \geq (1 - \beta)k/2$. Let U' be a subset of U of size $(1 - \beta)k/2$. Now the first inequality in Lemma 23 implies that

$$|N^+(U)| \geq |N^+(U')| \geq k/2 - 5d'k - 1 \stackrel{(1)}{\geq} (|U| + \beta k/13) - 5d'k - 1 > |U| + |S| + |T| + |C_{\text{small}}|,$$

a contradiction again. \square

Let S' be the set obtained from S by adding C_{small} and D_{small} . So $|S'| \leq 17\eta k$ and S', C', D' is a vertex partition of H .

Now let L (for ‘left’) be the set obtained from C' by adding all those vertices v from S' which satisfy $|N_H^+(v) \cap C'| \geq \eta'k$ and $|N_H^-(v) \cap C'| \geq \eta'k$. Next, let R (for ‘right’) be the set obtained from D' by adding all those remaining vertices v from S' which satisfy $|N_H^+(v) \cap D'| \geq \eta'k$ and $|N_H^-(v) \cap D'| \geq \eta'k$. Then $H[L]$ and $H[R]$ are both still $\eta'k$ -connected. We write M_V (for ‘vertical middle’) for the remaining vertices in S' (i.e. those which were not added to C' or D'). Then $|M_V| \leq |S'| \leq 17\eta k$. Moreover, L, M_V and R partition the vertex set of $R_{C''}$.

We also define another partition of $V(R_{C''})$ into three sets which we call T, M_H and B (for ‘top’, ‘horizontal middle’, and ‘bottom’) as follows:

- a cluster belongs to T if and only if its successor in F belongs to L ;
- a cluster belongs to M_H if and only if its successor in F belongs to M_V ;
- a cluster belongs to B if and only if its successor in F belongs to R .

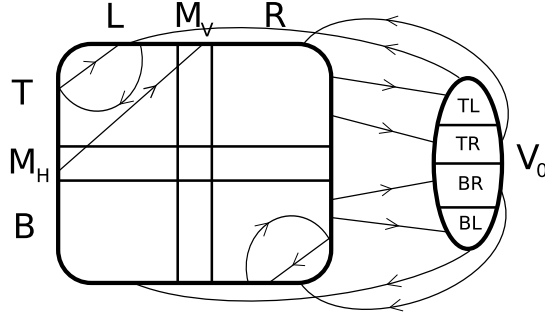


FIGURE 1. Shifted components and the exceptional set

The general picture (including a partition of V_0 defined below) is illustrated in Figure 1. For each of the above subsets of $V(H) = V(R_{G''})$ we use a ‘tilde’ notation to denote the subset of $V(G)$ consisting of the union of the corresponding clusters, thus $\tilde{L} = \cup_{U \in L} U \subseteq V(G)$, etc. Note that

$$|M_H| = |M_V| \leq 17\eta k. \quad (2)$$

We need to remove certain cycles from F that would create difficulties later on. Let $M := M_V \cup M_H$. We say that a cycle C of F *significantly intersects* M if $|C \cap M| \geq |C|/10$. If we have $|\tilde{M}| \leq |V_0|/\gamma^3$ then we remove all cycles that significantly intersect M from F and add all vertices in their clusters to the exceptional set. Since $d \ll \gamma$ we still have the inequality

$$|V_0| \leq 11d^{1/2}n + 10 \cdot 11d^{1/2}n/\gamma^3 \leq d^{1/4}n. \quad (3)$$

Later we will distinguish the following two cases according to the size of \tilde{M} .

- (\star) $|\tilde{M}| \leq |V_0|/\gamma^3$. Moreover, no cycle of F significantly intersects M .
- ($\star\star$) $|\tilde{M}| \geq |V_0|/\gamma^3 > 0$.

(The proof would be considerably simpler if we could remove all the cycles which significantly intersect/lie in M in the case ($\star\star$), but this would make $|V_0|$ too large.) Since any cycle in F has equal intersection sizes with M_H and M_V we still have $|M_H| = |M_V|$ of size at most $17\eta n$. We still denote the remaining subset of R by R , and similarly for all the other sets B, L, M_V etc.

8.2. Properties of the shifted components. We start by justifying the name ‘shifted components’. The following lemma shows that we have decomposed most of the digraph into two pieces of roughly equal size, where in each piece we have the high connectivity that enabled us to establish the result in the previous section.

Lemma 27.

- (i) $H[L]$ and $H[R]$ are strongly $\eta'k/2$ -connected.
- (ii) $|\tilde{L}|, |\tilde{R}|, |\tilde{B}|, |\tilde{T}| = n/2 \pm 19\eta n$.

Proof. To prove (i), recall that before the removal of the cycles we knew that $H[L]$ and $H[R]$ were strongly $\eta'k$ -connected. By (3), the number of clusters removed in case (\star) is at most $d^{1/4}n/m \leq \eta'k/2$. Since we only removed entire F -cycles, we did not delete any edges from H other than those incident to the clusters that were deleted. Thus for each cluster removed the connectivity only decreases by at most one.

For (ii), we recall that $|C| = k/2 \pm 2\eta k$ (Lemma 24) and L was obtained from C by removing $|C_{\text{small}}| \leq 8\eta k$ clusters, adding at most $|S'| \leq 17\eta k$ clusters and removing at most $d^{1/4}n/m \leq \eta k$ clusters. The argument for R is the same. The other two bounds follow since $|B| = |R|$ and $|T| = |L|$. \square

Next we define a partition of M_V into M_V^{LR} and M_V^{RL} as follows. A cluster $X \in M_V$ belongs to M_V^{LR} if $|N_H^+(X) \cap C'| < \eta'k$ and $|N_H^-(X) \cap D'| < \eta'k$. A cluster $X \in M_V$ belongs to M_V^{RL}

if $|N_H^+(X) \cap D'| < \eta'k$ and $|N_H^-(X) \cap C'| < \eta'k$. The definition of L and R and the fact that H has minimum semidegree at least $\beta k/2$ imply that this is indeed a partition of M_V . Since $|M_V| \leq 17\eta k$ and $\delta^\pm(H) \geq \beta k/2$ we have the following properties.

Lemma 28.

- (i) All $V \in M_V^{LR}$ satisfy $|N_H^+(V) \cap L|, |N_H^-(V) \cap R| < 2\eta'k$ and $|N_H^+(V) \cap R|, |N_H^-(V) \cap L| > \beta k/3$.
- (ii) All $V \in M_V^{RL}$ satisfy $|N_H^+(V) \cap R|, |N_H^-(V) \cap L| < 2\eta'k$ and $|N_H^+(V) \cap L|, |N_H^-(V) \cap R| > \beta k/3$.

Let M_H^{LR} the set of clusters whose successor in F belongs to M_V^{LR} and define M_H^{RL} similarly. Note that this yields a partition of M_H .

It will be helpful later to note that if $M_V^{LR} \neq \emptyset$ then we can use clusters in M_V^{LR} to obtain shifted walks from L to R . Similarly, any clusters in M_V^{RL} can be used to obtain shifted walks from R to L . This will use the following lemma.

Lemma 29.

- (i) For all $x \in \widetilde{M}_H^{LR}$, we have $|N_G^+(x) \cap \widetilde{L}| \leq 3\eta'n$ and $|N_G^+(x) \cap \widetilde{R}| \geq \beta n/2$. Also, at most $12\eta'n$ vertices in \widetilde{L} have more than $|\widetilde{M}_H^{LR}|/4$ inneighbours in \widetilde{M}_H^{LR} .
- (ii) For all $x \in \widetilde{M}_V^{LR}$, we have $|N_G^-(x) \cap \widetilde{B}| \leq 3\eta'n$ and $|N_G^-(x) \cap \widetilde{T}| \geq \beta n/2$. Also, at most $12\eta'n$ vertices in \widetilde{B} have more than $|\widetilde{M}_V^{LR}|/4$ outneighbours in \widetilde{M}_V^{LR} .
- (iii) For all $x \in \widetilde{M}_H^{RL}$, we have $|N_G^+(x) \cap \widetilde{R}| \leq 3\eta'n$ and $|N_G^+(x) \cap \widetilde{L}| \geq \beta n/2$. Also, at most $12\eta'n$ vertices in \widetilde{R} have more than $|\widetilde{M}_H^{RL}|/4$ inneighbours in \widetilde{M}_H^{RL} .
- (iv) For all $x \in \widetilde{M}_V^{RL}$, we have $|N_G^-(x) \cap \widetilde{T}| \leq 3\eta'n$ and $|N_G^-(x) \cap \widetilde{B}| \geq \beta n/2$. Also, at most $12\eta'n$ vertices in \widetilde{T} have more than $|\widetilde{M}_V^{RL}|/4$ outneighbours in \widetilde{M}_V^{RL} .

Proof. For (i), suppose $x \in \widetilde{M}_H^{LR}$ satisfies $|N_G^+(x) \cap \widetilde{L}| \geq 3\eta'n$. Note that Lemma 21 implies that x is typical. Using the definition of ‘typical’ and accounting for vertices added to V_0 we still have $|N_{G''}^+(x) \cap \widetilde{L}| \geq 2\eta'n$. Then the cluster U containing x must have (in $R_{G''}$) at least $2\eta'k$ outneighbours in L . The definition of M_H^{LR} implies that the successor U^+ of U lies in M_V^{LR} . Then $|N_H^+(U^+) \cap L| = |N_{R_{G''}}^+(U) \cap L| \geq 2\eta'k$, contradicting Lemma 28(i). We deduce that $|N_G^+(x) \cap \widetilde{L}| \leq 3\eta'n$. It follows that there are at most $3\eta'n|\widetilde{M}_H^{LR}|$ edges from \widetilde{M}_H^{LR} to \widetilde{L} , so the final assertion of (i) holds. For the second bound in (i), we note that

$$|N_G^+(x) \cap \widetilde{R}| \geq \delta^+(G) - |N_G^+(x) \cap \widetilde{L}| - |\widetilde{M}_V| - |V_0| \geq \beta n - 3\eta'n - 17\eta n - d^{1/4}n \geq \beta n/2.$$

For (ii), suppose $x \in \widetilde{M}_V^{LR}$ satisfies $|N_G^-(x) \cap \widetilde{B}| \geq 3\eta'n$. Then the cluster $U \in M_V^{LR}$ containing x must have (in $R_{G''}$) at least $2\eta'k$ inneighbours in B . Thus in H it has at least $2\eta'k$ inneighbours in R , contradicting Lemma 28(i). The remainder of (ii) follows as for (i). The proof of (iii) is very similar to that of (i) and the proof of (iv) to that of (ii). \square

If X and Y are clusters in L , then there are many shifted walks (with respect to $R_{G''}$ and F) from X to Y . Later we will need that paths corresponding to such walks can be found in G , even if a large number of vertices in clusters lying on these paths have already been used for other purposes. This will follow from the following lemma.

Lemma 30. *Suppose U is a cluster, $u \in U$ and write $s = \eta'k/4$.*

- (i) If $U \in R \cup M_V^{RL}$ then there are clusters $V_1, \dots, V_s \in B$ such that $V_i U \in E(R_{G''})$ and u has at least $d'm/4$ inneighbours in V_i for $1 \leq i \leq s$.
- (ii) If $U \in T \cup M_H^{RL}$ then there are clusters $V_1, \dots, V_s \in L$ such that $UV_i \in E(R_{G''})$ and u has at least $d'm/4$ outneighbours in V_i for $1 \leq i \leq s$.
- (iii) If $U \in L \cup M_V^{LR}$ then there are clusters $V_1, \dots, V_s \in T$ such that $V_i U \in E(R_{G''})$ and u has at least $d'm/4$ inneighbours in V_i for $1 \leq i \leq s$.

- (iv) If $U \in B \cup M_H^{LR}$ then there are clusters $V_1, \dots, V_s \in R$ such that $UV_i \in E(R_{G''})$ and u has at least $d'm/4$ outneighbours in V_i for $1 \leq i \leq s$.

Proof. To prove (i) recall from Lemma 27 that $H[R]$ is strongly $\eta'k/2$ -connected, and so has minimum indegree at least $\eta'k/2$. Thus any $U \in R$ has inneighbours V_1, \dots, V_{2s} in $R_{G''}$ such that $V_i \in B$. This also holds for $U \in M_V^{RL}$ by Lemma 28(ii), since $\beta \gg \eta'$. In both cases we remove all the V_i for which u does not have at least $d'm/4$ inneighbours in V_i . Then, since u is typical (this was defined before Lemma 21), we are left with $2s - \varepsilon^{1/2}k \geq s$ clusters where u has at least $d'm/4$ inneighbours. Statements (ii)–(iv) are proved similarly. \square

8.3. Transitions. As in the highly connected case, our general strategy is to find a suitable shifted walk W and transform it into a Hamilton cycle. We will be able to move easily within \tilde{L} , and also within \tilde{R} , using the same arguments as in the highly connected case. However, we need other methods to move between \tilde{L} and \tilde{R} , which we will now discuss. To avoid excessive notation we will just describe how to move from \tilde{R} to \tilde{L} , as our arguments will be symmetric under the exchange $R \leftrightarrow L$ (and so $B \leftrightarrow T$). To move from \tilde{R} to \tilde{L} we use two types of ‘transitions’ from \tilde{B} to \tilde{L} . The first of these is a set of edges Match_{BL} from \tilde{B} to \tilde{L} , which will ‘almost’ be a matching, and will have certain desirable properties defined as follows.

Given matchings Match' and Match'' in G from \tilde{B} to \tilde{L} , we call a cluster V *full* (with respect to $\text{Match}' \cup \text{Match}''$) if it contains at least γm endvertices of edges in $\text{Match}' \cup \text{Match}''$. Given a number ℓ , we say V is ℓ -*fair* (with respect to $\text{Match}' \cup \text{Match}''$) if no cluster with distance at most ℓ from V in F is full. A cluster V is ℓ -*excellent* if it is ℓ -fair and no cluster with distance at most ℓ from V in F lies in $M = M_V \cup M_H$ (the ‘middle’). We call $\text{Match}' \cup \text{Match}''$ a *pseudo-matching from \tilde{B} to \tilde{L}* if the following properties are satisfied:

- $\text{Match}' \cup \text{Match}''$ is a vertex-disjoint union of ‘components’, each of which is either a single edge or a directed path of length 2.
- Every single edge component has at least one endvertex in a 4-excellent cluster, and every directed path of length 2 has both endvertices in 4-excellent clusters.

Given matchings Match' and Match'' from \tilde{T} to \tilde{R} , we say that $\text{Match}' \cup \text{Match}''$ is a *pseudo-matching from \tilde{T} to \tilde{R}* if it satisfies the analogous properties. As we shall see later, each edge of a pseudo-matching from \tilde{B} to \tilde{L} allows us to move from \tilde{R} to \tilde{L} . Note that this applies even to the two edges in any directed paths of length 2: these will enable us to move twice from \tilde{R} to \tilde{L} , using the rerouting procedure described later. Similarly, each edge of a pseudo-matching from \tilde{T} to \tilde{R} allows us to move from \tilde{L} to \tilde{R} . We consider pseudo-matchings rather than matchings because in general $\tilde{B} \cap \tilde{L} \neq \emptyset$, so the largest matching we can guarantee is only half as large as the largest pseudo-matching. This would not provide all the edges we need to move from \tilde{R} to \tilde{L} .

We now choose pseudo-matchings Match_{BL} from \tilde{B} to \tilde{L} and Match_{TR} from \tilde{T} to \tilde{R} , each of which is maximal subject to the condition

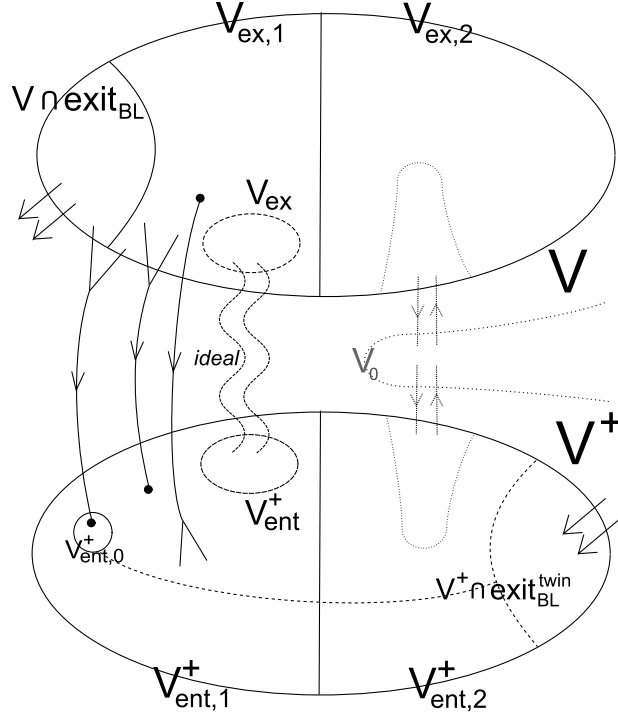
- $|\text{Match}_{BL}|, |\text{Match}_{TR}| \leq \gamma^2 n$.

(Here $|\text{Match}_{BL}|$ denotes the number of edges in Match_{BL} .) Note that Match_{BL} and Match_{TR} may have common vertices. Recalling that $|M| \leq 34\eta k$ by (2),

at most $2|\text{Match}_{BL}|/\gamma m \leq 3\gamma k$ clusters are full with respect to Match_{BL} , and at most $11(3\gamma k + |M|) \leq 400\eta k$ clusters are not 5-excellent with respect to Match_{BL} . A similar \clubsuit statement holds for Match_{TR} .

From now on, whenever we refer to a fair or excellent cluster it will be with respect to the pseudomatching Match_{BL} .

As in the highly connected case, we will identify ‘entries’ and ‘exits’ for edges of the cycle that do not lie in a pair corresponding to an edge of F . For Match_{BL} , the *exits* is the set exit_{BL}

FIGURE 2. Partitions avoiding interference between exits/entries and V_0 .

of all initial vertices of edges in Match_{BL} , and the *entries* is the set entry_{BL} of all final vertices of edges in Match_{BL} . (We will define further exits and entries in due course.)

At this stage, we do not know how many of the matching edges we actually will need in W , as this depends on a partition of the exceptional set V_0 to be defined in the next subsection. So, given a cluster V , we want to ensure if e.g. we only use some of the vertices in $V \cap \text{exit}_{BL}$, then the unused remainder of V and V^+ still forms a super-regular pair. We may not be able to achieve this for any V , but if V is 2-fair, we know that none of V^-, V, V^+ is full, which gives us the flexibility we need. We say that a cluster V is *nearly 2-fair* if V is either 2-fair or at distance 1 on F from a 2-fair cluster. In the following lemma we choose partitions of the nearly 2-fair clusters which allow us to avoid any ‘interference’ between exits/entries and the exceptional set. Figure 2 illustrates these partitions, and also some additional sets that will be defined in Subsection 8.5 (‘twins’ of exits/entries and an ideal to preserve super-regularity).

We define our partitions of the nearly 2-fair clusters as follows. For every 2-fair cluster V with $V \cap \text{exit}_{BL} \neq \emptyset$ we will choose a partition $V_{ex,1}, V_{ex,2}$ of V and a partition $V_{ent,1}^+, V_{ent,2}^+$ of V^+ . Also, for every 2-fair cluster V with $V \cap \text{entry}_{BL} \neq \emptyset$ we choose a partition $V_{ent,1}, V_{ent,2}$ of V and a partition $V_{ex,1}^-, V_{ex,2}^-$ of V^- . There is no conflict in our notation, i.e. we will not e.g. define $V_{ex,1}$ twice, since when $V \cap \text{exit}_{BL} \neq \emptyset$ we must have $V \in B$, whereas when $V^+ \cap \text{entry}_{BL} \neq \emptyset$ we must have $V^+ \in L$, so $V \in T$, and these cannot occur simultaneously. We also define the analogous partitions with respect to Match_{TR} , although for simplicity we will not explicitly introduce notation for them, as we will mainly focus on the case when only Match_{BL} is needed for the argument. So for each cluster V we will choose at most 4 partitions. We let $V_{2\text{nd}}$ be the intersection of all the second parts of the at most 4 partitions defined for V . (So if all 4 partitions are defined, then $V_{2\text{nd}}$ is the intersection of the sets $V_{ex,2}, V_{ent,2}$ defined with respect to Match_{BL} and the 2 analogous sets defined with respect to Match_{TR} . If only 3 partitions are defined for V , then $V_{2\text{nd}}$ is the intersection of only 3 sets etc. If no partition is defined for V , then $V_{2\text{nd}} = V$.) We let $X_{2\text{nd}}$ be the union of $V_{2\text{nd}}$ over all clusters V . We choose these partitions to satisfy the following lemma.

Lemma 31. *The partitions $V_{ex,1}, V_{ex,2}$ and $V_{ent,1}, V_{ent,2}$ can be chosen with the following properties (when they are defined).*

- (i) $|V_{ex,1}| = m/2$, $|V_{ent,1}| = m/2$.
- (ii) *For any 2-fair cluster V with $V \cap \text{exit}_{BL} \neq \emptyset$ we have $V_{ex,2} \cap \text{exit}_{BL} = \emptyset$. Moreover, there is a set $V_{ent,0}^+ \subseteq V_{ent,1}^+$ of size at most $10\epsilon m$ such that:*
 - Each vertex in $V^+ \setminus V_{ent,0}^+$ has at least $dm/40$ inneighbours in $V_{ex,1} \setminus \text{exit}_{BL}$.
 - Each vertex in $V_{ent,0}^+$ has at least $dm/8$ inneighbours in $V_{ex,1}$.
 - Each vertex in V has at least $dm/20$ outneighbours in $V_{ent,1}^+$.
- (iii) *For any 2-fair cluster V with $V \cap \text{entry}_{BL} \neq \emptyset$ we have $V_{ent,2} \cap \text{entry}_{BL} = \emptyset$. Moreover, there is a set $V_{ex,0}^- \subseteq V_{ex,1}^-$ of size at most $10\epsilon m$ such that:*
 - Each vertex in $V^- \setminus V_{ex,0}^-$ has at least $dm/40$ outneighbours in $V_{ent,1} \setminus \text{entry}_{BL}$.
 - Each vertex in $V_{ex,0}^-$ has at least $dm/8$ outneighbours in $V_{ent,1}$.
 - Each vertex in V has at least $dm/20$ inneighbours in $V_{ex,1}^-$.

Also, the analogues of statements (i)–(iii) for Match_{TR} hold. Moreover,

- (iv) *Every vertex in V_0 has at least $\beta n/20$ inneighbours and at least $\beta n/20$ outneighbours in $X_{2\text{nd}}$.*
- (v) *If $d_{(1-\beta)n/2}^+(G) \geq n/2$ then there are sets $S'_B \subseteq \tilde{B} \cap X_{2\text{nd}}$ and $S'_T \subseteq \tilde{T} \cap X_{2\text{nd}}$ such that $|S'_B|, |S'_T| \geq \beta n/80$ and such that every vertex in $S'_B \cup S'_T$ has outdegree at least $n/2$ in G .*
- (vi) *If $d_{(1-\beta)n/2}^-(G) \geq n/2$ then there are sets $S'_L \subseteq \tilde{L} \cap X_{2\text{nd}}$ and $S'_R \subseteq \tilde{R} \cap X_{2\text{nd}}$ such that $|S'_L|, |S'_R| \geq \beta n/80$ and such that every vertex in $S'_L \cup S'_R$ has indegree at least $n/2$ in G .*

Proof. Consider a 2-fair cluster V with $V \cap \text{exit}_{BL} \neq \emptyset$. If $|V \cap \text{exit}_{BL}| < 20\epsilon m$ we set $V_{ent,0}^+ = \emptyset$. Otherwise, if $|V \cap \text{exit}_{BL}| \geq 20\epsilon m$ we define $V_{ent,0}^+$ to be the set of vertices in V^+ that have less than $\frac{d}{8}|V \setminus \text{exit}_{BL}|$ inneighbours in $V \setminus \text{exit}_{BL}$. Recall that $(V, V^+)_{G'}$ is $(10\epsilon, d/4)$ -super-regular. Since V is 2-fair we deduce that $|V_{ent,0}^+| \leq 10\epsilon m$.

Now consider constructing a partition of V into $V_{ex,1}$ and $V_{ex,2}$ as follows. Include $V \cap \text{exit}_{BL}$ into $V_{ex,1}$ and distribute the remaining vertices of V between $V_{ex,1}$ and $V_{ex,2}$ so that $|V_{ex,1}| = m/2$ (recall that m is even), choosing uniformly at random between all possibilities. Note that since V is 2-fair the probability that a vertex of $V \setminus \text{exit}_{BL}$ is included in $V_{ex,1}$ is at least $1/3$. Then by the Chernoff bound for the hypergeometric distribution (Proposition 9), with high probability each vertex in $V^+ \setminus V_{ent,0}^+$ has at least $\frac{1}{4}\frac{d}{8}|V \setminus \text{exit}_{BL}| \geq dm/40$ inneighbours in $V_{ex,1} \setminus \text{exit}_{BL}$. Also, by definition of $V_{ent,0}^+$ and super-regularity, each vertex in $V_{ent,0}^+$ has at least $dm/4 - \frac{d}{8}|V \setminus \text{exit}_{BL}| \geq dm/8$ inneighbours in $V_{ex,1}$. Next, consider similarly constructing a partition of V^+ into $V_{ent,1}^+$ and $V_{ent,2}^+$ as follows. Include $V_{ent,0}^+$ into $V_{ent,1}^+$ and distribute the remaining vertices of V^+ uniformly at random between $V_{ent,1}^+$ and $V_{ent,2}^+$ so that $|V_{ent,1}^+| = m/2$. Note that any vertex in V has outdegree at least $dm/4 - |V_{ent,0}^+| \geq dm/5$ in $V^+ \setminus V_{ent,0}^+$. Again, the probability that a given vertex from $V^+ \setminus V_{ent,0}^+$ is included in $V_{ent,1}^+$ is at least $1/3$, so with high probability each vertex in V has at least $(dm/5)/4 = dm/20$ outneighbours in $V_{ent,1}^+$. This shows the existence of the partitions required for (ii). The existence of partitions satisfying (iii) is proven in the same way.

For each vertex v in a cluster V which does not lie in $\text{exit}_{BL} \cup V_{ent,0} \cup \text{entry}_{BL} \cup V_{ex,0}$ or the analogous set defined with respect to Match_{TR} , the probability that it lies in the second part of each of the (up to) 4 partitions defined on V (and thus lies in $X_{2\text{nd}}$) is at least $(1/2)^4$. Since $\delta^0(G) \geq \beta n$, a Chernoff bound (Proposition 9) implies that we can also choose the partitions to satisfy (iv).

Now suppose that $d_{(1-\beta)n/2}^+(G) \geq n/2$. Then G contains at least $(1 + \beta)n/2$ vertices of outdegree at least $n/2$. So Lemma 27(ii) implies that \tilde{B} contains a set $\tilde{B}'_{\text{large}}$ of at least $\beta n/3$

vertices whose outdegree in G is at least $n/2$. $\tilde{B}'_{\text{large}}$ in turn contains a set \tilde{B}_{large} of at least $\beta n/4$ vertices which do not lie in $\text{exit}_{BL} \cup V_{\text{ent},0} \cup \text{entry}_{BL} \cup V_{\text{ex},0}$ (for any cluster V) or in the analogous set defined with respect to Match_{TR} . Similarly as for (iv), with high probability we have $|\tilde{B}_{\text{large}} \cap X_{2\text{nd}}| \geq (\beta n/4)/20$. Similar arguments applied to \tilde{T} , \tilde{L} and \tilde{R} show that we can choose the partitions to satisfy (v) and (vi). \square

8.4. The exceptional set. Next we will assign each vertex x in the exceptional set V_0 an *in-type* which is one of T or B and an *out-type* which is one of L or R . Combining these two types together we will say each vertex of V_0 gets a type of the form TR, TL, BR or BL . We will also abuse notion and think of TL as the set of all vertices of V_0 of in-type T and out-type L , etc. We write \tilde{T}^* for the set of all those vertices which belong to the set $X_{2\text{nd}}$ defined in the previous subsection as well as to clusters of T which are 5-excellent with respect to both Match_{BL} and Match_{TR} . The other sets \tilde{B}^* etc. are defined similarly.

Lemma 32. *We can assign each vertex $x \in V_0$ an in- and an out-type such that the following conditions are satisfied.*

- (i) *There is a matching Match_T from \tilde{T}^* to the set of vertices of in-type T .*
- (ii) *There is a matching Match_B from \tilde{B}^* to the set of vertices of in-type B .*
- (iii) *There is a matching Match_L from the set of vertices of out-type L to \tilde{L}^* .*
- (iv) *There is a matching Match_R from the set of vertices of out-type R to \tilde{R}^* .*
- (v) *The endvertices of the matchings $\text{Match}_T, \text{Match}_B, \text{Match}_L, \text{Match}_R$ in $V(G) \setminus V_0$ are all distinct. Let V_0^* denote the set of all these endvertices.*
- (vi) *No cluster of R_G contains more than γm vertices of V_0^* .*
- (vii) *Subject to the above conditions, $||TR| - |BL||$ is minimal.*

Proof. To show that such a choice is possible, we claim that we can proceed sequentially through the vertices of V_0 , assigning in-types and out-types and greedily extending the appropriate matchings. Since $|V_0| \leq d^{1/4}n$ by (3), at any stage in this process we have constructed at most $2d^{1/4}n$ edges of the matchings $\text{Match}_T, \text{Match}_B, \text{Match}_L, \text{Match}_R$, and so there are at most $2d^{1/4}n/\gamma \leq d^{1/5}n$ vertices belonging to clusters which contain at least γm endpoints of the matchings. In addition, we have to avoid all the at most $800\eta n$ vertices lying in clusters which are not 5-excellent with respect to both Match_{BL} and Match_{TR} . So in total we have to avoid at most $801\eta n$ vertices in each step. But by Lemma 31(iv) each exceptional vertex has in- and outdegree at least $\beta n/20$ in $X_{2\text{nd}}$, so Lemma 27(ii) implies that any vertex has at least $\beta n/50$ inneighbours in $\tilde{T} \cap X_{2\text{nd}}$ or at least $\beta n/50$ inneighbours in $\tilde{B} \cap X_{2\text{nd}}$. A similar statement holds for outneighbours in $\tilde{L} \cap X_{2\text{nd}}$ or $\tilde{R} \cap X_{2\text{nd}}$. Thus a greedy procedure can satisfy conditions (i)–(vi), and then we can choose an assignment to satisfy (vii). \square

Note that one advantage of choosing V_0^* in $X_{2\text{nd}}$ is that V_0^* will be disjoint from the sets Entry_{BL} etc. The strategy of the remaining proof depends on the value of $|TR| - |BL|$. We will only consider the case $|TR| - |BL| \geq 0$, as the argument for $|TR| - |BL| \leq 0$ is identical, under the symmetry $L \leftrightarrow R, T \leftrightarrow B$. When $|TR| > |BL|$ only Match_{BL} is needed for the argument. When $|TR| = |BL|$ we do not need either pseudo-matching, although the case $|TR| = |BL| = 0$ has additional complications.

8.5. Twins. When $|TR| > |BL|$, we obtain one type of transitions from \tilde{B} to \tilde{L} by fixing a pseudo-matching $\text{Match}'_{BL} \subseteq \text{Match}_{BL}$. The other type of transitions uses a set $\text{Entry}_{RL} \subseteq \tilde{M}_V^{RL}$, as explained below. We define exits $\text{Exit}_{BL} \subseteq \text{exit}_{BL}$ and entries $\text{Entry}_{BL} \subseteq \text{entry}_{BL}$ of Match'_{BL} as for Match_{BL} . Lemma 34(i) below implies that $|\text{Match}_{BL}| + |\tilde{M}_V^{RL}| \geq |TR| - |BL|$. Thus we can fix sets Match'_{BL} and Entry_{RL} to satisfy

$$|\text{Match}'_{BL}| + |\text{Entry}_{RL}| = |TR| - |BL|.$$

For each edge $xy \in \text{Match}'_{BL}$ we will choose ‘twins’ x^{twin} and y^{twin} of its endpoints. To use the edge xy in our shifted walk W , we will enter the cycle of F containing x at x^{twin} , wind around the cycle to x , use the edge xy , wind around the cycle containing y , and then leave it at y^{twin} . A vertex that is the midpoint of a directed path of length 2 in Match'_{BL} will actually have two twins, but we will not complicate the notation to reflect this, as it will be clear from the context which twin is intended. Thus we obtain two ‘twin maps’ $x \mapsto x^{twin}$ and $y \mapsto y^{twin}$. We also use the notation $S^{twin} = \{x^{twin} : x \in S\}$ when S is a set of vertices. The twin maps will be injective on Exit_{BL} and on Entry_{BL} , in that $|\text{Exit}_{BL}| = |\text{Exit}_{BL}^{twin}|$, $|\text{Entry}_{BL}| = |\text{Entry}_{BL}^{twin}|$, and moreover $|V \cap \text{Exit}_{BL}| = |V^+ \cap \text{Exit}_{BL}^{twin}|$, $|V \cap \text{Entry}_{BL}| = |V^- \cap \text{Entry}_{BL}^{twin}|$.

Our choice of x^{twin} depends on whether the cluster V containing x is 2-fair with respect to Match_{BL} . If V is not 2-fair then we fix arbitrary perfect matchings in G' from V^- to V and from V to V^+ (using Lemma 12). Then for every $x \in V \cap \text{Exit}_{BL}$ we let x^{twin} be the vertex x is matched to in V^+ and for every $x \in V \cap \text{Entry}_{BL}$ we let x^{twin} be the vertex in V^- matched to x .

On the other hand, if V is 2-fair then we make use of the partitions defined in Lemma 31. If $V \cap \text{Exit}_{BL} \neq \emptyset$ then we choose twins for vertices in $V \cap \text{Exit}_{BL}$ within $(V_{ent,2}^+ \cup V_{ent,0}^+) \setminus V_0^*$, arbitrarily subject to the condition that if $|V \cap \text{Exit}_{BL}| > 20\epsilon m$ then $(V \cap \text{Exit}_{BL})^{twin}$ contains $V_{ent,0}^+$. (Recall that V_0^* was defined in Lemma 32(v).) If V is 2-fair, we will also choose some ideal of $(V \setminus \text{Exit}_{BL}, V^+ \setminus \text{Exit}_{BL}^{twin})_{G'}$ to create flexibility when selecting further sets while preserving super-regularity. To do this, recall that $(V, V^+)_{G'}$ was $(10\epsilon, d/4)$ -super-regular. Together with Lemma 31(i),(ii) this implies that $(V_{ex,1} \setminus \text{Exit}_{BL}, V_{ent,1}^+ \setminus \text{Exit}_{BL}^{twin})_{G'}$ is $(30\epsilon, d/40)$ -super-regular. Next we randomly choose sets $V_{ex} \subseteq V_{ex,1} \setminus \text{Exit}_{BL}$ and $V_{ent}^+ \subseteq V_{ent,1}^+ \setminus \text{Exit}_{BL}^{twin}$ of size $80dm$. Lemma 15 (applied with $\theta = 160d$ and $n = m/2$) implies that with high probability (V_{ex}, V_{ent}^+) is an $(\sqrt{\epsilon}, d^2)$ -ideal for $(V_{ex,1} \setminus \text{Exit}_{BL}, V_{ent,1}^+ \setminus \text{Exit}_{BL}^{twin})_{G'}$. Moreover, Lemma 31(ii) and the Chernoff bound (Proposition 9) together imply that with high probability every vertex in $V_{ex,2}$ has at least d^2m outneighbours in V_{ent}^+ while every vertex in $V_{ent,2}^+$ has at least d^2m inneighbours in V_{ex} . Altogether this shows that we can choose (V_{ex}, V_{ent}^+) to be a $(\sqrt{\epsilon}, d^2)$ -ideal for $(V \setminus \text{Exit}_{BL}, V^+ \setminus \text{Exit}_{BL}^{twin})_{G'}$.

Similarly, if $V \cap \text{Entry}_{BL} \neq \emptyset$ then we choose twins for vertices in $V \cap \text{Entry}_{BL}$ in $(V_{ex,2}^- \cup V_{ex,0}^-) \setminus V_0^*$, arbitrarily subject to the condition that if $|V \cap \text{Entry}_{BL}| > 20\epsilon m$ then $(V \cap \text{Entry}_{BL})^{twin}$ contains $V_{ex,0}^-$. We also choose a $(\sqrt{\epsilon}, d^2)$ -ideal (V_{ex}^-, V_{ent}^-) for $(V^- \setminus \text{Entry}_{BL}^{twin}, V \setminus \text{Entry}_{BL})_{G'}$. Then we define X_{BL} to be the union of the sets V_{ex} and V_{ent} defined using Match'_{BL} over all nearly 2-fair clusters V . Note that these sets will play a similar role to the sets V^* used in the highly connected case, in that they preserve super-regularity even if when some vertices are deleted. We let

$$X_{BL}^* := X_{BL} \cup \text{Exit}_{BL} \cup \text{Entry}_{BL} \cup \text{Exit}_{BL}^{twin} \cup \text{Entry}_{BL}^{twin}.$$

Note that $X_{BL}^* \cap V_0^* = \emptyset$. Define X_{TR} and X_{TR}^* similarly using the matching Match'_{TR} .

We will also choose twins for vertices in Entry_{RL} such that if $x \in V \in M_V^{RL}$ then $x^{twin} \in V^- \in M_H^{RL}$. Lemma 29(iii),(iv) implies that each $x \in \text{Entry}_{RL}$ has many inneighbours in \tilde{B} while x^{twin} has many outneighbours in \tilde{L} . Writing C for the cycle of F containing the cluster containing x , we get a transition from \tilde{B} to \tilde{L} by entering C at x from an inneighbour in \tilde{B} , traversing C , then exiting C at x^{twin} to an outneighbour in \tilde{L} .

Now we describe how to choose twins for Entry_{RL} , and also some ideals to create flexibility while preserving super-regularity. Call a cluster V M^{RL} -full if it contains at least γm vertices in Entry_{RL} . Say V is ℓ -good (with respect to Match_{BL} and Entry_{RL}) if V is ℓ -fair with respect to Match_{BL} and no cluster with distance at most ℓ from V on F is M^{RL} -full. Since $|\text{Entry}_{RL}| \leq |V_0| \leq d^{1/4}n$ the number of M^{RL} -full clusters is at most $\gamma^{-1}d^{1/4}n/m$. Recalling that by \clubsuit at most $3\gamma k$ clusters are full,

$$\text{at most } 9(3\gamma k + \gamma^{-1}d^{1/4}n/m) \leq 30\gamma k \text{ clusters are not 4-good.} \quad (\diamond)$$

Consider a cluster $V \in M_V^{RL}$ with $V \cap \text{Entry}_{RL} \neq \emptyset$. If V is not 2-good then we choose a perfect matching in G' from V^- to V (using Lemma 12), and for each $x \in V$ let x^{twin} be the vertex in V^- that is matched to x . Now suppose that V is 2-good. Then none of V^- , V and V^+ is full with respect to Match_{BL} or M^{RL} -full. Since $(V^-, V)_{G'}$ is $(10\varepsilon, d/4)$ -super-regular and $|V \cap \text{Entry}_{RL}| < \gamma m$ we can apply Lemma 14 to obtain a set $Y \subseteq V^-$ with $|Y| = |V \cap \text{Entry}_{RL}|$ such that $(V^- \setminus Y, V \setminus \text{Entry}_{RL})_{G'}$ is $(20\varepsilon, d/8)$ -super-regular. Then we let the twin map be an arbitrary bijection from $V \cap \text{Entry}_{RL}$ to Y . Next we apply Lemma 15 with $\theta = 32d$ to obtain a $(\sqrt{\varepsilon}, d^2)$ -ideal for $(V^- \setminus \text{Entry}_{RL}^{twin}, V \setminus \text{Entry}_{RL})_{G'}$, which we will call (V_{ex}^-, V_{ent}) . (Similarly to the earlier argument and the one in the next paragraph, the partitions of $V(G) \setminus V_0$ into \tilde{L} , \tilde{R} and \tilde{M}_V and into \tilde{T} , \tilde{B} and \tilde{M}_H guarantee that there is no conflict with our previous notation.) Now we define

$$\begin{aligned} X_{RL}^* &:= \bigcup_{V \in M_V^{RL}} V_{ent} \cup \bigcup_{V \in M_H^{RL}} V_{ex} \cup \text{Entry}_{RL} \cup \text{Entry}_{RL}^{twin}, \\ X^* &:= X_{BL}^* \cup X_{RL}^*. \end{aligned} \quad (4)$$

Then $|X^*| \leq \gamma n$ and $X^* \cap V_0^* = \emptyset$. (The latter follows since the vertices in V_0^* lie in 5-excellent clusters and so $X_{RL}^* \cap V_0^* = \emptyset$.) We also define

$$\begin{aligned} V_{entry} &:= V \cap (\text{Entry}_{BL} \cup \text{Exit}_{BL}^{twin} \cup \text{Entry}_{RL}), \\ V_{exit} &:= V \cap (\text{Exit}_{BL} \cup \text{Entry}_{BL}^{twin} \cup \text{Entry}_{RL}^{twin}). \end{aligned}$$

Note that $\text{Entry}_{BL} \subseteq \tilde{L}$, $\text{Exit}_{BL}^{twin} \subseteq \tilde{R}$ and $\text{Entry}_{RL} \subseteq \tilde{M}_V^{RL}$. Since \tilde{L} , \tilde{R} and \tilde{M}_V partition $V(G) \setminus V_0$, any vertex will be used at most once to enter a cluster. In particular,

$$V_{entry} = \begin{cases} V \cap \text{Entry}_{BL} & \text{if } V \in L; \\ V \cap \text{Exit}_{BL}^{twin} & \text{if } V \in R; \\ V \cap \text{Entry}_{RL} & \text{if } V \in M_V^{RL}. \end{cases}$$

Similarly, $\text{Exit}_{BL} \subseteq \tilde{B}$, $\text{Entry}_{BL}^{twin} \subseteq \tilde{T}$ and $\text{Entry}_{RL}^{twin} \subseteq \tilde{M}_H^{RL}$. Since \tilde{T} , \tilde{B} and \tilde{M}_H also partition $V(G) \setminus V_0$, any vertex will be used at most once to exit a cluster and

$$V_{exit} = \begin{cases} V \cap \text{Exit}_{BL} & \text{if } V \in B; \\ V \cap \text{Entry}_{BL}^{twin} & \text{if } V \in T; \\ V \cap \text{Entry}_{RL}^{twin} & \text{if } V \in M_H^{RL}. \end{cases}$$

Some vertices may be used for both exits and entrances, and they will have two twins. We summarise the properties of twins with the following lemma.

Lemma 33. *Suppose that $|TR| > |BL|$. Then*

- (i) $|\text{Match}'_{BL}| + |\text{Entry}_{RL}| = |TR| - |BL|$.
- (ii) *Every cluster intersects at most one of Entry_{BL} , Exit_{BL}^{twin} , Entry_{RL} . Similarly, every cluster intersects at most one of Exit_{BL} , Entry_{BL}^{twin} , Entry_{RL}^{twin} .*
- (iii) *There exists a perfect matching from $V \setminus V_{exit}$ to $V^+ \setminus V_{entry}^+$.*
- (iv) *Suppose V is 3-good with respect to Match_{BL} and Entry_{RL} . Then*
 - *For all sets X' and Y' with $(V \cap X^*) \setminus V_{exit} \subseteq X' \subseteq V \setminus V_{exit}$ and $(V^+ \cap X^*) \setminus V_{entry}^+ \subseteq Y' \subseteq V^+ \setminus V_{entry}^+$ the pair $(X', Y')_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular.*
 - *For all sets X' and Y' with $(V \cap X^*) \setminus V_{entry} \subseteq X' \subseteq V \setminus V_{entry}$ and $(V^- \cap X^*) \setminus V_{exit}^- \subseteq Y' \subseteq V^- \setminus V_{exit}^-$ the pair $(Y', X')_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular.*

Proof. As discussed at the beginning of the subsection, Lemma 34(i) will allow us to choose Match'_{BL} and Entry_{RL} of the size required in (i). Property (ii) was discussed above. We will just consider the first point of property (iv), as the second is similar. Suppose V is 3-good and consider sets X' and Y' as in the statement. We need to show that $(X', Y')_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular. If $V \cap \text{Entry}_{RL}^{twin} \neq \emptyset$ this holds by definition of X_{RL}^* since $V_{ex} \cap V_{exit} = \emptyset$ and $V_{ent}^+ \cap V_{entry}^+ = \emptyset$ by (ii) (and so $V_{ex} \subseteq X'$ and $V_{ent}^+ \subseteq Y'$), and since V^+ is 2-good. If $V \cap \text{Exit}_{BL} \neq$

\emptyset this holds by definition of X_{BL}^* , since V is 2-fair, and similarly, if $V \cap \text{Entry}_{BL}^{\text{twin}} \neq \emptyset$ this holds again by definition of X_{BL}^* , since V^+ is 2-fair. It remains to prove property (iii). Suppose first that $V \in M_H^{RL}$. If V^+ is not 2-good then the required matching exists by the way we defined twins for Entry_{RL} in this case. On the other hand, if V^+ is 2-good then we can apply the super-regularity property (iv) just established (which only used the fact that V^+ is 2-good) and Lemma 12. Next suppose that $V \in B$. Then $V_{\text{exit}} = V \cap \text{Exit}_{BL}$ and $V_{\text{entry}}^+ = V^+ \cap \text{Exit}_{BL}^{\text{twin}}$. Thus if V is not 2-fair then the required matching exists by the way we defined twins for Match'_{BL} in this case. On the other hand, if V is 2-fair then we can apply the first point of property (iv), which only used the fact that V is 2-fair. Similarly, when $V \in T$, then $V_{\text{exit}} = V \cap \text{Entry}_{BL}^{\text{twin}}$ and $V_{\text{entry}}^+ = V^+ \cap \text{Entry}_{BL}$. If V^+ is not 2-fair the required matching exists by the construction in this case, whereas if V^+ is 2-fair then we can apply the second point of property (iv) with (V, V^+) playing the role of (V^-, V) , which only uses the fact that V^+ (playing the role of V in the second point) is 2-fair. \square

8.6. Summary. The auxiliary graph H is decomposed into shifted components L ‘left’ and R ‘right’ of size $k/2 \pm 19\eta k$ and a set M_V of size $|M_V| < 17\eta k$. This corresponds to a partition of $V(G) \setminus V_0 = \tilde{L} \cup \tilde{R} \cup \tilde{M}_V$. The 1-factor F defines a partition $V(H) = T \cup B \cup M_H$, where a cluster V belongs to T, B, M_H if and only if its successor V^+ belongs to L, R, M_V respectively. The shifted walk W will use two types of transitions from \tilde{B} to \tilde{L} . One type is a pseudo-matching Match'_{BL} from \tilde{B} to \tilde{L} , matching Exit_{BL} to Entry_{BL} . The other type is a set Entry_{RL} of vertices in $\tilde{M}_V^{RL} \subseteq \tilde{M}_V$, with the property that if $V \in \tilde{M}_V^{RL}$ then any $x \in V$ has many inneighbours in \tilde{B} and any $y \in V^-$ has many outneighbours in \tilde{L} . We did not discuss transitions from \tilde{T} to \tilde{R} , but these are obtained similarly under the transformation $L \leftrightarrow R, B \leftrightarrow T$, etc. Each vertex in these sets has a twin (or possibly two twins) that will be used when W traverses the cycle of F containing it. For any cluster V , the set of exit points from V is V_{exit} and the set of entry points to V is V_{entry} . There exists a perfect matching from $V \setminus V_{\text{exit}}$ to $V^+ \setminus V_{\text{entry}}^+$. The exceptional set V_0 is decomposed into 4 parts TR, TL, BR and BL , where the first letter gives the in-type of a vertex and the second letter the out-type: there is a matching Match_T from \tilde{T}^* to vertices of in-type T (and so on). Technical complications are created by the possibility that a cluster may be full (contain at least γm endpoints of Match_{BL}) or M^{RL} -full (contain at least γm endpoints of Entry_{RL}). A cluster V is ℓ -fair if no cluster at distance at most ℓ from V is full, ℓ -excellent if no cluster at distance at most ℓ from V is full or in $M = M_V \cup M_H$, and ℓ -good if no cluster at distance at most ℓ from V is full or M^{RL} -full. We have a set $X^* = X_{BL}^* \cup X_{RL}^*$ such that whenever V is 3-good, we have flexibility to use any vertices avoiding these sets in V^-, V and V^+ (as well as avoiding the exits and entries already chosen), while preserving super-regularity of the corresponding pairs in F . Finally, the set V_0^* of endpoints in $V(G) \setminus V_0$ of the matchings Match_T etc. only uses 5-excellent clusters and avoids X^* .

9. THE SIZE OF THE PSEUDO-MATCHING

Our aim in this section is to prove the following lower bound on the size of our pseudo-matchings Match_{BL} and Match_{TR} .

Lemma 34.

- (i) $|\text{Match}_{BL}| \geq \min\{|\tilde{M}_V^{LR}|/2, \gamma^4 n\} - |\tilde{M}_V^{RL}| - |V_0|$. Moreover, if $|TR| > |BL|$ then $|\text{Match}_{BL}| \geq |TR| - |BL| - |\tilde{M}_V^{RL}| + \min\{|\tilde{M}_V^{LR}|/2, \gamma^4 n\}$.
- (ii) $|\text{Match}_{TR}| \geq \min\{|\tilde{M}_V^{RL}|/2, \gamma^4 n\} - |\tilde{M}_V^{LR}| - |V_0|$. Moreover, if $|BL| > |TR|$ then $|\text{Match}_{TR}| \geq |BL| - |TR| - |\tilde{M}_V^{LR}| + \min\{|\tilde{M}_V^{RL}|/2, \gamma^4 n\}$.

To prove this we first show that there are large sets $S_B \subseteq \tilde{B}$ with many outneighbours in \tilde{L} and $S_L \subseteq \tilde{L}$ with many inneighbours in \tilde{B} . Note that part (v) in the following lemma is not used in the proof of Lemma 34 but will be needed in the final section of the paper.

Lemma 35.

(i) If $|TR| > |BL|$ there is $S_B \subseteq \tilde{B}$ with $|S_B| \geq \beta n/100$, such that every $x \in S_B$ satisfies

$$|N_G^+(x) \cap \tilde{L}| \geq \deg_L := \frac{n}{2} - (|BL| + |BR| + |\tilde{R}|) - |\tilde{M}_V^{RL}| - |\tilde{M}_V^{LR}|/4.$$

Furthermore, in any case, \tilde{B} contains a set S_B^* of size $|S_B^*| \geq \beta n/100$, such that every $x \in S_B^*$ satisfies $|N_G^+(x) \cap \tilde{L}| \geq \frac{n}{2} - |V_0| - |\tilde{R}| - |\tilde{M}_V^{RL}| - |\tilde{M}_V^{LR}|/4$.

(ii) If $|TR| > |BL|$ there is $S_L \subseteq \tilde{L}$ with $|S_L| \geq \beta n/100$, such that every $x \in S_L$ satisfies

$$|N_G^-(x) \cap \tilde{B}| \geq \deg_B := \frac{n}{2} - (|TL| + |BL| + |\tilde{T}|) - |\tilde{M}_H^{RL}| - |\tilde{M}_H^{LR}|/4.$$

Furthermore, in any case, \tilde{L} contains a set S_L^* of size $|S_L^*| \geq \beta n/100$, such that every $x \in S_L^*$ satisfies $|N_G^-(x) \cap \tilde{B}| \geq \frac{n}{2} - |V_0| - |\tilde{T}| - |\tilde{M}_H^{RL}| - |\tilde{M}_H^{LR}|/4$.

(iii) If $|BL| > |TR|$ there is $S_T \subseteq \tilde{T}$ with $|S_T| \geq \beta n/100$, such that every $x \in S_T$ satisfies

$$|N_G^+(x) \cap \tilde{R}| \geq \deg_R := \frac{n}{2} - (|TL| + |TR| + |\tilde{L}|) - |\tilde{M}_V^{LR}| - |\tilde{M}_V^{RL}|/4.$$

Furthermore, in any case, \tilde{T} contains a set S_T^* of size $|S_T^*| \geq \beta n/100$, such that every $x \in S_T^*$ satisfies $|N_G^+(x) \cap \tilde{R}| \geq \frac{n}{2} - |V_0| - |\tilde{L}| - |\tilde{M}_V^{LR}| - |\tilde{M}_V^{RL}|/4$.

(iv) If $|BL| > |TR|$ there is $S_R \subseteq \tilde{R}$ with $|S_R| \geq \beta n/100$, such that every $x \in S_R$ satisfies

$$|N_G^-(x) \cap \tilde{T}| \geq \deg_T := \frac{n}{2} - (|TR| + |BR| + |\tilde{B}|) - |\tilde{M}_H^{LR}| - |\tilde{M}_H^{RL}|/4.$$

Furthermore, in any case, \tilde{R} contains a set S_R^* of size $|S_R^*| \geq \beta n/100$, such that every $x \in S_R^*$ satisfies $|N_G^-(x) \cap \tilde{T}| \geq \frac{n}{2} - |V_0| - |\tilde{B}| - |\tilde{M}_H^{LR}| - |\tilde{M}_H^{RL}|/4$.

(v) Finally, suppose that M_V^{RL} , TR and BL are all empty.

- If $|\tilde{L} \cup TL| \geq |\tilde{B} \cup BR|$, then \tilde{B} contains a set S_B of at least $\beta n/100$ vertices, each having at least $|\tilde{M}_V^{LR}|/4$ outneighbours in $\tilde{L} \cup TL$.
- If $|\tilde{L} \cup TL| \leq |\tilde{B} \cup BR|$, then \tilde{L} contains a set S_L of at least $\beta n/100$ vertices, each having at least $|\tilde{M}_V^{LR}|/4$ inneighbours in $\tilde{B} \cup BR$.

Proof. Suppose that $|TR| > |BL|$. To prove (i), we first consider the case when $d_{(1-\beta)n/2}^+(G) \geq n/2$. Let S'_B be as defined in Lemma 31(v). Let S_B be the set obtained from S'_B by deleting the following vertices.

- The set V_0^* of $2|V_0| \leq 2d^{1/4}n$ endvertices in $V(G) \setminus V_0$ of edges in Match_T , Match_B , Match_L , Match_R .
- All the at most $800\eta n$ vertices which lie in clusters that are not 5-excellent with respect to Match_{BL} or Match_{TR} .
- All the at most $2|V_0|k/(\gamma m/2) \leq d^{1/5}n$ vertices which lie in clusters containing at least $\gamma m/2$ vertices of V_0^* .
- All the at most $12\eta'n$ vertices in \tilde{B} having more than $|\tilde{M}_V^{LR}|/4$ outneighbours in \tilde{M}_V^{LR} (see Lemma 29(ii)).

Thus $|S_B| \geq \beta n/100$. Now we make the following key use of the minimality of $|TR| - |BL| > 0$. We claim that any vertex $x \in S_B$ has outdegree at most $|BL| + |BR|$ in V_0 . Otherwise, there would be some edge xy with $y \in TL \cup TR$. But then we can change the in-type of y to B by deleting the edge in Match_T incident to y and adding the edge xy to Match_B . Conditions (v) and (vi) in Lemma 32 will still hold, since S_B is disjoint from V_0^* and only contains vertices in clusters containing at most $\gamma m/2$ vertices of V_0^* . Condition (ii) holds since $x \in \tilde{B}^*$ by definition of S_B . This reduces $||TR| - |BL||$, which contradicts the minimality condition in Lemma 32(vii). Therefore the claim holds. Now recall that $\tilde{R} \cup \tilde{L} \cup \tilde{M}_V^{LR} \cup \tilde{M}_V^{RL} \cup V_0$ is a partition of $V(G)$. Any $x \in S_B$ has at least $n/2$ outneighbours, of which at most $|\tilde{R}| + |\tilde{M}_V^{RL}|$ belong to $\tilde{R} \cup \tilde{M}_V^{RL}$,

at most $|\widetilde{M}_V^{LR}|/4$ belong to \widetilde{M}_V^{LR} and at most $|BL| + |BR|$ belong to V_0 . This shows that S_B is a set as required in (i).

Now consider the case when $d_{(1-\beta)n/2}^+(G) < n/2$, and so $d_{(1-\beta)n/2}^-(G) \geq (1+\beta)n/2$ by our degree assumptions. Then G has at least $(1+\beta)n/2$ vertices of indegree at least $(1+\beta)n/2$, and by Lemma 27 at least $(1+\beta)n/2 - |\widetilde{R}| - |V_0| - |\widetilde{M}_V| > \beta n/3$ of these belong to \widetilde{L} . Let $A \subseteq \widetilde{L}$ be a set of $\beta n/3$ vertices with indegree at least $(1+\beta)n/2$. Note that every vertex in A has indegree at least $(1+\beta)n/2 + |\widetilde{B}| - n > \beta n/3$ in \widetilde{B} . Then we must have a set S_B of at least $\beta n/100$ vertices in \widetilde{B} , each having outdegree at least $\beta^3 n$ in A , or we would have $\beta n/3 \cdot |A| \leq E(\widetilde{B}, A) \leq \beta n/100 \cdot |A| + \beta^3 n |\widetilde{B}|$, a contradiction. Then every vertex in S_B has at least $\beta^3 n \geq \frac{n}{2} - |\widetilde{R}|$ outneighbours in $A \subseteq \widetilde{L}$, as required. This completes the proof of (i) when $|TR| > |BL|$.

The argument for (i) when we do not have $|TR| > |BL|$ is the same, except that we no longer have the minimality argument for $||TR| - |BL||$, so vertices in S_B^* may have all of V_0 as outneighbours. The arguments for (ii)–(iv) are analogous, so we omit them.

Finally, suppose that M_V^{RL} , TR and BL are all empty, so that $\widetilde{R} \cup \widetilde{L} \cup \widetilde{M}_V^{LR} \cup TL \cup BR$ is a partition of $V(G)$. For the first point in (v), suppose that $|\widetilde{L} \cup TL| \geq |\widetilde{B} \cup BR|$. Since $|\widetilde{B}| = |\widetilde{R}|$, every vertex x in S_B (defined as above) has at least $n/2 - |BR| - |\widetilde{B}| - |\widetilde{M}_V^{LR}|/4$ outneighbours in $\widetilde{L} \cup TL$. By assumption, we have $|BR| + |\widetilde{B}| + |\widetilde{M}_V^{LR}|/2 \leq n/2$, so the number of outneighbours of x in $\widetilde{L} \cup TL$ is at least $|\widetilde{M}_V^{LR}|/4$, as required. The second point follows in the same way. \square

Proof of Lemma 34. Observe that all stated lower bounds are at most $\gamma^2 n$, so it is enough to prove the existence of pseudo-matchings satisfying these bounds. We will suppose that $|TR| > |BL|$ and prove the ‘moreover’ statement of (i); the arguments for the other assertions are similar. Define an auxiliary bipartite graph whose vertex classes are \widetilde{B} and \widetilde{L} by joining a vertex $x \in \widetilde{B}$ to a vertex $y \in \widetilde{L}$ if xy is an edge of G . Let J be the graph obtained from this bipartite graph by deleting all the edges whose endvertices both lie in clusters having distance at most 4 in F from M . Let Q be the largest matching in J .

Case 1. $|Q| \geq \gamma^2 n$.

Let Q' be a matching obtained from Q by deleting as few edges as possible so as to ensure that every vertex of G belongs to at most one edge from Q' . Note that every vertex of G has indegree at most 1 and outdegree at most 1 in Q , so Q considered as a subdigraph of G is a vertex-disjoint union of directed paths and cycles. Thus we can retain at least $1/3$ of the edges of Q in Q' (with equality for a disjoint union of directed triangles). By deleting further edges if necessary we may assume that $|Q'| = \gamma^2 n/3$.

We claim that there is a submatching Q'' of Q' of size at least $\gamma|Q'|/3$ such that no cluster is full with respect to Q'' (i.e. every cluster contains at most γm endvertices of Q''). To see that such a Q'' exists, consider the submatching Q'' obtained from Q' by retaining every edge of Q' with probability $\gamma/2$ in Q'' , independently of all other edges of Q' . Then for any cluster V , the expected number of endvertices of Q'' in V is at most $\gamma m/2$, and the expected size of Q'' is $\gamma|Q'|/2$. By Chernoff bounds we see that with high probability Q'' has the claimed properties.

Note that Q'' is a pseudo-matching from \widetilde{B} to \widetilde{L} , as by construction it is a matching, and by definition of J every edge in Q'' has an endvertex in a 4-excellent cluster. Also, since $|V_0| \leq d^{1/4} n$ we have $|Q''| \geq \gamma^3 n/9 \geq |V_0| + \gamma^4 n \geq |TR| - |BL| - |\widetilde{M}_V^{RL}| + \gamma^4 n$, as required.

Case 2. $|Q| \leq \gamma^2 n$.

Let A be a minimum vertex cover of J . Then $|A| \leq \gamma^2 n$ by König’s theorem (Proposition 6). Write $A_B := A \cap \widetilde{B}$ and $A_L := A \cap \widetilde{L}$. We say that a cluster V is A -full if it contains at least $\gamma m/3$ vertices from A . We say that V is A -excellent if no cluster of distance at most 4 from V on F is A -full or lies in M . Note that at most $\gamma^2 n/(\gamma m/3) = 3\gamma n/m$ clusters are A -full and thus by (2)

all but at most $9(3\gamma n + |M|m) \leq 350\eta n$ vertices lie in A -excellent clusters. Since $|TR| > |BL|$ we can construct the sets S_B and S_L given by Lemma 35(i) and (ii). Let S'_B be the set of all those vertices in $S_B \setminus A$ which lie in A -excellent clusters. Thus $|S'_B| \geq |S_B| - \gamma^2 n - 350\eta n \geq \beta n/101$. Moreover, $N_G^+(S'_B) \cap \tilde{L} \subseteq A_L$, since none of the edges deleted in the construction of J were incident to S'_B .

Now we greedily choose a matching Match_1 from S'_B to $A_L \subseteq \tilde{L}$ of size \deg_L (defined in Lemma 35(i)) in such a way that every cluster contains at most $\gamma m/3$ vertices on the \tilde{B} -side of J . To see that this is possible, note that at any stage in the process we have excluded at most $|A|/(\gamma m/3) < \beta n/101 \leq |S'_B|$ vertices in S'_B , so we can always pick a suitable vertex x in S'_B . Then, since we have chosen less than \deg_L vertices in A_L , we can choose an unused outneighbour of x in \tilde{L} (which lies in the cover A , so in A_L).

Let S'_L be the set of all those vertices in $S_L \setminus A$ which lie in A -excellent clusters and are not endvertices of edges in Match_1 . Then $|S'_L| \geq |S_L| - \gamma^2 n - 350\eta n - 2|\text{Match}_1| \geq \beta n/101$ and $N_G^-(S'_L) \cap \tilde{B} \subseteq A_B$. As before, we can greedily choose a matching Match_2 from $A_B \subseteq \tilde{B}$ to S'_L of size \deg_B in such a way that every cluster contains at most $\gamma m/3$ vertices on the \tilde{L} -side of J .

Note that every A -excellent cluster is 4-excellent with respect to $\text{Match}_1 \cup \text{Match}_2$, as it contains at most γm endvertices of edges from $\text{Match}_1 \cup \text{Match}_2$ (it is not A -full), and so is not full with respect to $\text{Match}_1 \cup \text{Match}_2$. Also, any edge e in $\text{Match}_1 \cup \text{Match}_2$ has one endvertex in A and one endvertex outside A . The endvertex outside A is that in S'_B (if $e \in \text{Match}_1$) or S'_L (if $e \in \text{Match}_2$). So the endvertex outside A is not an endvertex of another edge from $\text{Match}_1 \cup \text{Match}_2$ and lies in a cluster which is 4-excellent with respect to $\text{Match}_1 \cup \text{Match}_2$. We deduce that $\text{Match}_1 \cup \text{Match}_2$ is a disjoint union of edges and directed paths of length 2 satisfying the definition of a pseudo-matching from \tilde{B} to \tilde{L} . Moreover, since $|\tilde{M}_V^{RL}| = |\tilde{M}_H^{RL}|$ and $|\tilde{M}_V^{LR}| = |\tilde{M}_H^{LR}|$, we have

$$\begin{aligned} |\text{Match}_1 \cup \text{Match}_2| &= \deg_L + \deg_B \\ &= n - (2|BL| + |BR| + |TL| + |\tilde{R}| + |\tilde{T}|) - 2|\tilde{M}_V^{RL}| - 2|\tilde{M}_V^{LR}|/4 \\ &= |TR| - |BL| + (n - |V_0| - |\tilde{R}| - |\tilde{L}|) - 2|\tilde{M}_V^{RL}| - |\tilde{M}_V^{LR}|/2 \\ &= |TR| - |BL| + |\tilde{M}_V| - 2|\tilde{M}_V^{RL}| - |\tilde{M}_V^{LR}|/2 \\ &= |TR| - |BL| - |\tilde{M}_V^{RL}| + |\tilde{M}_V^{LR}|/2, \end{aligned}$$

as required. The proof of the first statement of (i) is the same, except that we use the ‘furthermore’ statements of Lemma 35(i) and (ii) in the final calculation instead of working with \deg_L and \deg_B . \square

10. PROOF OF THEOREM 5

In this section we use the matchings and sets constructed in Section 8 to prove Theorem 5. We will assume that H is not strongly ηk -connected, as we have already covered this case in Section 7 (although it could also be deduced from the arguments in this section). Our strategy will depend on the value of $|TR| - |BL|$, and also on the size of middle, as described by the cases (\star) or $(\star\star)$ above. We divide the proof into three subsections: the first covers the case when $|TR| \neq |BL|$ and (\star) holds, the second when $(\star\star)$ holds, and the third when $|TR| = |BL|$ and (\star) holds.

10.1. The case when $|TR| \neq |BL|$ and (\star) holds. We will just give the argument for the case when $|TR| > |BL|$, as the other case is similar. We recall that (\star) is the case when $|\tilde{M}| \leq |V_0|/\gamma^3$ and $|C \cap M| < |C|/10$ for every cycle C of F . In this case we will use the pseudo-matching Match'_{BL} as well as the additional transitions from \tilde{B} to \tilde{L} which we get from $\text{Entry}_{RL} \cup \text{Entry}_{RL}^{\text{twin}}$. We want to construct a walk W with the same properties as in the proof of the case when H is highly connected.

Recall that both $H[L]$ and $H[R]$ are strongly $\eta'k/2$ -connected (see Lemma 27). Then by arguing as in the proof of Lemma 22 for the graph $H[L]$ instead of H we deduce that for any two clusters $V, V' \in L$ we can find $\eta'^2k/64$ shifted walks (with respect to $R_{G''}$ and F) from V to V' such that each walk traverses at most $4/\eta'$ cycles from F and every cluster is internally used by at most one of these walks. A similar statement holds for any two clusters in R . For any two clusters V and V' , we call a shifted walk (with respect to $R_{G''}$ and F) from V to V' *useful* if it traverses at most $4/\eta'$ cycles from F and if every cluster which is internally used by the walk is 4-excellent (note that 4-excellence is defined with respect to pseudo-matching Match'_{BL} in this case, and the pseudo-matching Match_{TR} is irrelevant). Since all but at most $400\eta'k$ clusters are 4-excellent (by \clubsuit) we have the following property.

Whenever \mathcal{V} is a set of at most $\eta'^2k/100$ clusters and $V, V' \in L$ there exists a useful shifted walk from V to V' that does not internally use clusters in \mathcal{V} . A similar statement (\heartsuit) holds for any two clusters in R .

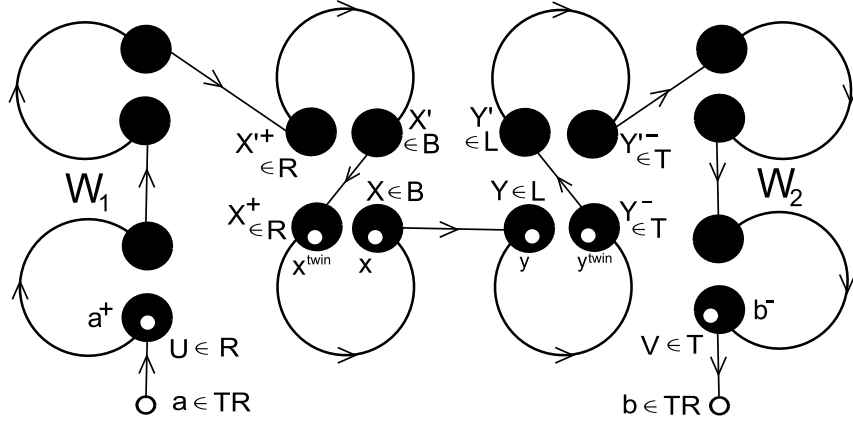
We incorporate the vertices of the exceptional set V_0 using whichever edges in the matchings $\text{Match}_T, \text{Match}_B, \text{Match}_L, \text{Match}_R$ correspond to their in-types and out-types. Suppose for example that we have just visited a vertex x of out-type L , arriving via some edge in Match_T or Match_B (depending on the in-type of x) and leaving to its outneighbour x^+ in the matching Match_L . Then x^+ belongs to some cluster U in L . Since $H[L]$ is highly connected we can proceed to incorporate any vertex y of in-type T as follows. Let y^- be the inneighbour of y in Match_T . Then y^- belongs to some cluster V of T , and so by definition of T the successor V^+ of V on F is a cluster of L . Let $W'_{xy} = X_1C_1X_1^-X_2C_2X_2^- \dots X_tC_tX_t^-X_{t+1}$ be a useful shifted walk with $X_1 = U$ and $X_{t+1} = V^+$. Let C_{t+1} be the cycle of F containing $X_{t+1} = V^+$ and form W_{xy} by appending the path in C_{t+1} from V^+ to V . So for any cycle C of F the clusters of C are visited equally often by W_{xy} . Then in the construction of W we can use the walk W_{xy} to move from x to y . Note that since we chose $\text{Match}_T, \text{Match}_B, \text{Match}_L, \text{Match}_R$ to use at most γm vertices from any cluster and since $|V_0|/(\gamma m) \ll \eta'^2k$, (\heartsuit) implies that we can avoid using any cluster more than $3\gamma m$ times (although we may visit a cluster more often).

Thus we see that the structure of H allows us to follow any vertex of out-type L with any vertex of in-type T , and similarly we can follow any vertex of out-type R with any vertex of in-type B . In particular, we can incorporate all vertices of type TL sequentially, all vertices of type BR sequentially, and vertices of type BL or TR can be incorporated in an alternating sequence, while there remain vertices of both types. This explains the purpose of condition (vii) in Lemma 32: choosing $||TR| - |BL||$ to be minimal.

We order the vertices of V_0 as follows. First, we list all vertices of type TL (if any exist). These will be followed by an arbitrary vertex of type TR (which must exist as $|TR| > |BL| \geq 0$). Then list all vertices of type BR (if any exist). Then we alternately list vertices of type BL and TR until all vertices of type BL are exhausted. Finally, we list all vertices of type TR (if any remain). So the list by type has the form:

$$TL, \dots, TL | TR | BR, \dots, BR | BL, TR, \dots, BL, TR | TR, \dots, TR.$$

We can follow the procedure described above to incorporate all vertices in the list apart from the final block of $|TR| - |BL| - 1$ vertices of type TR . At this point the above procedure would require a shifted walk from R to L , which need not exist. For these remaining vertices we will use the $|TR| - |BL|$ transitions from \tilde{B} to \tilde{L} formed by the matching Match'_{BL} and the vertices in $\text{Entry}_{RL} \cup \text{Entry}_{RL}^{\text{twin}}$. (We need $|TR| - |BL|$ transitions rather than $|TR| - |BL| - 1$ since we need to close the walk W after incorporating the last exceptional vertex.) Suppose we have just visited an exceptional vertex a of type TR , leaving to its outneighbour a^+ in the matching Match_R , and we want to visit another vertex b of type TR , with inneighbour b^- in the matching Match_T . Let U be the cluster of R containing a^+ and V the cluster of T containing b^- . We pick an unused edge xy of Match'_{BL} , where x belongs to a cluster X of B and y to a cluster Y of L . Recall from Subsection 8.3 that $x \in \text{exit}_{BL}$ and $y \in \text{entry}_{BL}$ have twins $x^{\text{twin}} \in X^+ \in R$

FIGURE 3. Transitions using Match_{BL}

and $y^{twin} \in Y^- \in T$. By Lemma 30 there are $X' \in B$ and $Y' \in L$ such that x^{twin} has at least $d'm/4$ inneighbours in X' , whereas y^{twin} has at least $d'm/4$ outneighbours in Y' . We can also choose X' and Y' to be 4-excellent, since by Lemma 30 there are at least $\eta'k/4$ choices for both X' and Y' , and at most $400\eta k \ll \eta'k/4$ clusters are not 4-excellent (by \clubsuit). Choose a useful shifted walk W_1 from U to the F -successor $(X')^+$ of X' and a useful shifted walk W_2 from Y' to the F -successor V^+ of V . W_1 and W_2 exist by \heartsuit , since $(X')^+ \in R$ as $X' \in B$ and $V^+ \in L$ as $V \in T$. Thus, as illustrated in Figure 3, we can form a segment of the walk W linking a to b by first following W_1 to $(X')^+$, then the path in F from $(X')^+$ to X' , then the edge $X'X^+$, then the path in F from X^+ to X , then the edge xy , then the path in F from Y to Y^- , then the edge Y^-Y' , then W_2 to V^+ , and finally the path in F from V^+ to V . When we are transforming our walk W into a Hamilton cycle we will replace $X'X^+$ with an edge of G from some vertex in X' to x^{twin} and replace Y^-Y' with an edge from y^{twin} to some vertex in Y' . So we say that x^{twin} is a *prescribed endvertex* for this particular occurrence of $X'X^+$ on W and that y^{twin} is a *prescribed endvertex* for this particular occurrence of Y^-Y' on W . The vertices x and y will be *prescribed endvertices* for the edge xy on W . (We will also define other prescribed endvertices on W , and if they are not endpoints of Match'_{BL} then they will always be such that they have at least $d'm/4$ inneighbours in the previous cluster on W or at least $d'm/4$ outneighbours in the next cluster on W . Note our eventual Hamilton cycle may not follow the route connecting x^{twin} , x , y and y^{twin} used here since we will use a rerouting procedure which is similar to that in the case when H is highly connected.)

We use different matching edges from Match'_{BL} for different vertices of type TR . After having used all of Match'_{BL} , we use the $|TR| - |BL| - |\text{Match}'_{BL}|$ transitions from \tilde{B} to \tilde{L} which we get from $\text{Entry}_{RL} \cup \text{Entry}_{RL}^{twin}$ instead. If $X \in M_V^{RL}$ is the cluster containing $x \in \text{Entry}_{RL}$ and so $X^- \in M_H^{RL}$ is the cluster containing its twin $x^{twin} \in \text{Entry}_{RL}^{twin}$, then, using Lemma 30 again, we can choose 4-excellent clusters $X' \in B$ and $X'' \in L$ such that x has at least $d'm/4$ inneighbours in X' whereas x^{twin} has at least $d'm/4$ outneighbours in X'' . We then take W_1 to be a useful walk from U to the F -successor $(X')^+$ of X' and W_2 to be a useful walk from X'' to V^+ . Then when we are transforming W into a Hamilton cycle we will replace $X'X$ with an edge of G from some vertex in X' to x and replace X^-X'' with an edge from x^{twin} to some vertex in X'' . So we say that x is a *prescribed endvertex* for this particular occurrence of $X'X$ on W and that x^{twin} is a *prescribed endvertex* for this particular occurrence of X^-X'' on W .

At the moment we have constructed a walk W which starts in the cluster $U^* \in T$ containing the inneighbour of the first exceptional vertex in our list, then goes into that vertex and then joins up all the exceptional vertices. After visiting the last exceptional vertex of type TR , W follows our last transition from \tilde{B} to \tilde{L} and ends in some 4-excellent cluster $V^* \in L$. (Using the same notation as above, if this last transition was a matching edge $xy \in \text{Match}'_{BL}$ then

$V^* = Y'$, and if it was a transition formed by a vertex $x \in \text{Entry}_{RL}$ and its twin x^{twin} then $V^* = X''$.) Say that a cluster V is *nearly 4-good* if V is either 4-good or at distance 1 on F from a 4-good cluster. (A nearly 4-good cluster is 3-good, but not conversely.) Note that since all walks above were useful, the walk W constructed only *uses* nearly 4-good clusters, except when it uses a prescribed endvertex. Using (\heartsuit) , it is easy to check that we can choose W in such a way that every nearly 4-good cluster is used at most $9\gamma m$ times.

Before closing up the walk W , we have to enlarge it by some special walks W_L^{bad} , W_L^{good} , W_R^{bad} and W_R^{good} which will ensure that we can actually transform W into a Hamilton cycle of G (rather than a 1-factor). We start by defining W_L^{good} . List the 4-good clusters in L as V_1, \dots, V_s , for some s , where $V_1 = V^*$. Choose useful shifted walks W_i from V_i to V_{i+1} , for $i = 1, \dots, s$, where $V_{s+1} := V^*$. Let $W_L^{\text{good}} := W_1 \dots W_s$. Then W_L^{good} is a shifted walk from V^* to itself, which uses every 4-good cluster in L at least once, and which only uses nearly 4-good clusters.

Call a cycle in F *bad* if it does not contain a 4-good cluster lying in $L \cup R$. For every bad cycle we pick a cluster whose distance from M on F is at least 2. (This is possible since we are in case (\star) , when no F -cycle significantly intersects M .) We let \mathcal{Z}_L and \mathcal{Z}_R be the sets of clusters in L and R thus obtained. Then no cluster $Z \in \mathcal{Z}_L \cup \mathcal{Z}_R$ is nearly 4-good, since Z has distance at least 2 from M on F , and so the neighbours of Z on F cannot be 4-good by definition of ‘bad’. In particular, no cluster in $\mathcal{Z}_L \cup \mathcal{Z}_R$ is 4-good, so $|\mathcal{Z}_L|, |\mathcal{Z}_R| \leq 30\gamma k$ by (\diamond) .

The purpose of the walk W_L^{bad} is to ‘fill up’ each cluster in \mathcal{Z}_L : W_L^{bad} will ensure that W enters each such cluster precisely m times. (Recall that this notion was defined in Section 5.) List the clusters in \mathcal{Z}_L that are not already entered m times as Z^1, \dots, Z^t , and let $a_i := m - |Z_{\text{entry}}^i|$, where Z_{entry}^i is as defined before the statement of Lemma 33. (Recall that Z^i is not nearly 4-good and so W only enters Z^i in vertices which are prescribed.) Let $U^i \in T$ be the F -predecessor of Z^i . Let $z_1^i, \dots, z_{a_i}^i$ be the vertices in $Z^i \setminus Z_{\text{entry}}^i$ and $u_1^i, \dots, u_{a_i}^i$ be the vertices in $U^i \setminus U_{\text{exit}}^i$. (Lemma 33(iii) implies that $|Z_{\text{entry}}^i| = |U_{\text{exit}}^i|$.) Apply Lemma 30 to choose 4-excellent clusters $Z_j^i \in T$ and $U_j^i \in L$ such that z_j^i has at least $d'm/4$ inneighbours in Z_j^i and such that u_j^i has at least $d'm/4$ outneighbours in U_j^i . We now find the following shifted walks:

- For each $i = 1, \dots, t$ and each $j = 1, \dots, a_i - 1$ choose a useful walk $W_{i,j}'$ from U_j^i to the F -successor $(Z_{j+1}^i)^+ \in L$ of Z_{j+1}^i .
- Choose a useful walk W_0'' from V^* to the F -successor $(Z_1^1)^+$ of Z_1^1 .
- For each $i = 1, \dots, t - 1$ choose a useful walk W_i'' from $U_{a_i}^i$ to the F -successor $(Z_1^{i+1})^+$ of Z_1^{i+1} .
- Choose a useful walk W_t'' from $U_{a_t}^t$ to V^* .
- Define the shifted walks $W_{i,j}'' := (Z_j^i)^+ C_j^i Z_j^i Z^i C^i U^i U_j^i$ for each $i = 1, \dots, t$ and each $j = 1, \dots, a_i$, where C_j^i is the F -cycle containing Z_j^i and where C^i is the F -cycle containing Z^i .

Then, as illustrated in Figure 4, we define

$$W_L^{\text{bad}} := W_0'' W_{1,1}'' W_{1,1}' W_{1,2}'' W_{1,2}' \dots W_{1,a_1-1}' W_{1,a_1}'' W_1'' W_{2,1}'' W_{2,1}' \dots W_{2,a_2-1}' \dots W_{t,a_t-1}' W_{t,a_t}'' W_t''.$$

So W_L^{bad} is a shifted walk from V^* to itself. When transforming our walk W into a Hamilton cycle of G , for each $i = 0, \dots, t - 1$ we will replace the edge $Z_j^i Z^i$ on $W_{i,j}''$ by an edge of G entering z_j^i and the edge $U^i U_j^i$ on $W_{i,j}''$ by an edge leaving u_j^i . So we say that z_j^i , u_j^i are *prescribed endvertices* for these particular occurrences of $Z_j^i Z^i$, $U^i U_j^i$.

Note that W_L^{bad} is composed of $1 + \sum_{i=1}^t 2a_i \leq 3tm \leq 90\gamma n$ walks, each using at most $8/\eta'$ clusters (by definition of useful walks). Also W_L^{good} is composed of at most $|L| \leq k$ further such walks. Using (\heartsuit) , we can choose W_L^{good} and W_L^{bad} such that the number of times they use

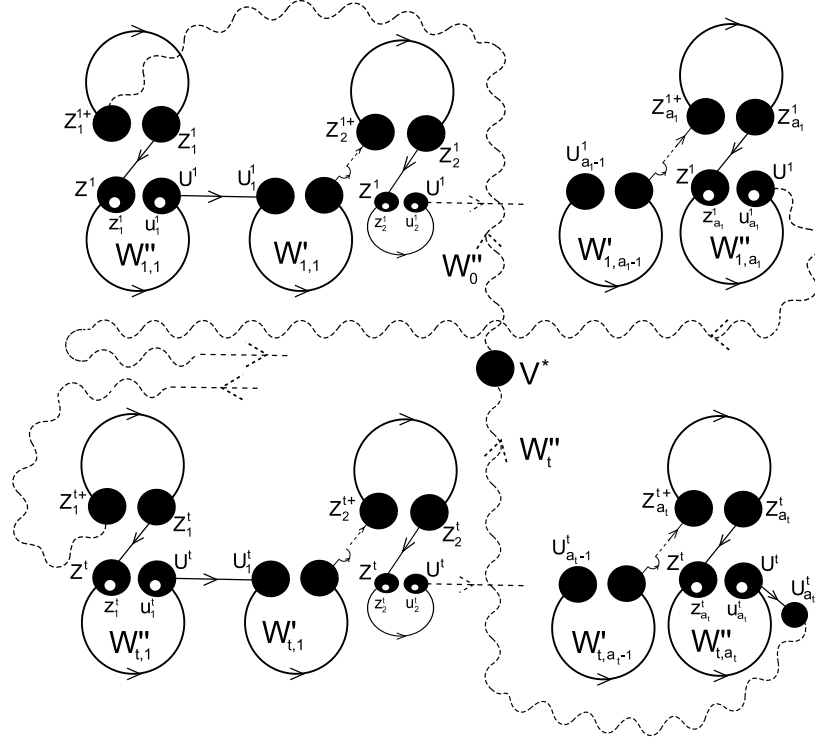


FIGURE 4. A bad walk

every cluster outside $\mathcal{Z}_L \cup \mathcal{Z}_L^-$ is at most $\frac{(90\gamma n+k)(8/\eta')}{\eta'^2 k/100} < \gamma^{1/2}m$ (say). Here \mathcal{Z}_L^- is the set of predecessors of \mathcal{Z}_L on F .

Let $V^{**} \in R$ be the cluster which contains the neighbour in Match_R of the first exceptional vertex of type TR in our list (this exists, since $|TR| > |BL|$). Then V^{**} is 4-excellent by Lemma 32. Define walks W_R^{good} and W_R^{bad} similarly to W_L^{good} and W_L^{bad} , where V^{**} now plays the role of V^* . (So both W_R^{good} and W_R^{bad} are walks from V^{**} to itself.) Now we construct our final walk, which we will also call W , as follows. We start with our previous walk W joining U^* to V^* , then we add $W_L^{good}W_L^{bad}$ and replace the occurrence of V^{**} mentioned above with $W_R^{good}W_R^{bad}$. We close up W by adding a useful walk from V^* to $(U^*)^+$, and then following the path in F from $(U^*)^+$ to U^* . Our final walk W has the properties listed below.

- (a) For each cycle C of F , W visits every cluster of C the same number of times, say m_C .
- (b'') • W enters every cluster of $R_{G''}$ at most m times, and thus W exits every cluster at most m times.
- If $V \in \mathcal{Z}_L \cup \mathcal{Z}_R$, then W enters V precisely m times and all the vertices of V are prescribed endvertices for these m entering edges of W . If $V \in \mathcal{Z}_L^- \cup \mathcal{Z}_R^-$, then W exits V precisely m times and all the vertices of V are prescribed endvertices for these m exiting edges of W .
- If $V \notin \mathcal{Z}_L \cup \mathcal{Z}_R$ is not nearly 4-good then W enters V precisely $|V_{entry}|$ times and the set V_{entry} is the set of prescribed endvertices for all these $|V_{entry}|$ entering edges of W . Similarly, if $V \notin \mathcal{Z}_L^- \cup \mathcal{Z}_R^-$ is not nearly 4-good then W exits V precisely $|V_{exit}|$ times and the set V_{exit} is the set of prescribed endvertices for all these $|V_{exit}|$ exiting edges of W .
- If V is nearly 4-good then W enters V between $|V_{entry}|$ and $|V_{entry}| + 2\gamma^{1/2}m$ times, the set V_{entry} is the set of prescribed endvertices for $|V_{entry}|$ of these entering edges of F and no vertex in V is a prescribed endvertex for the other entering edges of W . The analogue holds for the exits of W at V .

- (c) W visits every vertex of V_0 exactly once.
- (d) For each $x_i \in V_0$ we can choose an inneighbour x_i^- in the cluster preceding x_i on W and an outneighbour x_i^+ in the cluster following x_i on W , so that as x_i ranges over V_0 all vertices x_i^+ , x_i^- are distinct.

Recall that V_0^* denotes the set of all endvertices of the matching edges in $\text{Match}_B \cup \text{Match}_T \cup \text{Match}_L \cup \text{Match}_R$ outside of V_0 . Our aim now is to transform W into a Hamilton cycle of G . We start by fixing edges in G corresponding to all those edges of W that lie in $R_{G''}$ but not in F . We first do this for all those occurrences $VU \in E(R_{G''}) \setminus E(F)$ of edges on W for which there is no prescribed endvertex. Note that the second and third conditions in (b'') together imply that in this case both V and U must be nearly 4-good. Then, applying Lemma 12 as in Section 7, we can replace each such occurrence VU by an edge from $V \setminus (X^* \cup V_0^*)$ to $U \setminus (X^* \cup V_0^*)$ in G , so that all the edges of G obtained in this way are disjoint. We denote the set of edges obtained by \mathcal{E}_1 . Next we choose the edge in G for all those occurrences $VU \in E(R_{G''}) \setminus E(F)$ of edges on W which have a prescribed endvertex. This can be achieved by the following greedy procedure. Suppose that we have assigned the endvertex $u \in U$ to VU . Then V will be 4-excellent, so by the last condition in (b'') we have chosen at most $3\gamma^{1/2}m$ endvertices in V for edges constructed in previous steps. But u has at least $d'm/4$ inneighbours in V , where $d' \gg \gamma$, and $|V \cap (X^* \cup V_0^*)| \leq 2\gamma m$, so we can replace VU by vu for some $v \in V \setminus (X^* \cup V_0^*)$ which is distinct from all the vertices chosen before. (This is the point where we need to work with $R_{G''}$ instead of $R_{G'}$ – we have $d \ll \gamma$, and so the above argument would fail for $R_{G'}$.) We denote the set of edges obtained by \mathcal{E}_2 .

Let $\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2 \cup \mathcal{E}_3 \cup \mathcal{E}_4$, where $\mathcal{E}_3 = \text{Match}'_{BL}$ and $\mathcal{E}_4 = \text{Match}_B \cup \text{Match}_T \cup \text{Match}_L \cup \text{Match}_R$. (Note that W used each edge in $\mathcal{E}_3 \cup \mathcal{E}_4$ precisely once.) For each cluster V let $V_{Exit} \subseteq V$ be the subset of all initial vertices of edges in \mathcal{E} and let $V_{Entry} \subseteq V$ be the subset of all final vertices of edges in \mathcal{E} . Then $V_{exit} \subseteq V_{Exit}$ and $V_{entry} \subseteq V_{Entry}$. The following lemma provides useful properties of these fixed edges.

Lemma 36.

- (i) \mathcal{E} is a vertex-disjoint union of directed paths, each having at least one endvertex in a 4-excellent cluster.

Moreover, every cluster V satisfies the following.

- (ii) $|V_{Exit}| = |V_{Entry}^+|$.
- (iii) If V is nearly 4-good then $|V_{Exit}|, |V_{Entry}| \leq 4\gamma^{1/2}m$, $(V \cap X^*) \setminus V_{entry} \subseteq V \setminus V_{Entry}$ and $(V \cap X^*) \setminus V_{exit} \subseteq V \setminus V_{Exit}$. Moreover, $V_{Exit} \cap V_{Entry} = V_{exit} \cap V_{entry}$.
- (iv) If V is nearly 4-good then the pairs $(V \setminus V_{Exit}, V^+ \setminus V_{Entry}^+)_{G'}$ and $(V^- \setminus V_{Exit}^-, V \setminus V_{Entry})_{G'}$ are $(\sqrt{\varepsilon}, d^2)$ -super-regular.
- (v) There is a perfect matching from $V \setminus V_{Exit}$ to $V^+ \setminus V_{Entry}^+$.

Proof. By construction every vertex is the initial vertex of at most one edge in \mathcal{E} and the final vertex of at most one edge in \mathcal{E} , so \mathcal{E} is a disjoint union of directed paths and cycles. To prove statement (i), we note that \mathcal{E}_1 forms an independent set of edges in \mathcal{E} and each edge in \mathcal{E}_1 has both endvertices in 4-excellent clusters. Moreover, every edge in \mathcal{E}_2 has a prescribed endvertex, and if $u \in U$ was prescribed for an edge VU or UV in W , then V is a 4-excellent cluster and we chose $v \in V$ so that uv is the only edge of \mathcal{E} containing v . Thus any component of \mathcal{E} containing an edge from $\mathcal{E}_1 \cup \mathcal{E}_2$ is a directed path having at least one endvertex in a 4-excellent cluster. Also, \mathcal{E}_3 and \mathcal{E}_4 are vertex-disjoint, so any component of \mathcal{E} not containing an edge from $\mathcal{E}_1 \cup \mathcal{E}_2$ is either a component of \mathcal{E}_3 , which has the required property by definition of ‘pseudo-matching’, or a directed path consisting of two edges of \mathcal{E}_4 , which has the required property by Lemma 32. Thus statement (i) holds.

Condition (ii) follows immediately from our construction of W . The first part of (iii) follows from the last part of (b'') and the definition of 4-good clusters. To check the remainder of (iii), note that the last part of (b'') implies that the vertices in $V_{Exit} \setminus V_{exit}$ and in $V_{Entry} \setminus V_{entry}$

are endvertices of edges in $\mathcal{E}_1 \cup \mathcal{E}_4$ or non-prescribed endvertices of edges in \mathcal{E}_2 . We chose the endvertices of edges in \mathcal{E}_1 and the non-prescribed endvertices of edges in \mathcal{E}_2 to be disjoint from each other and from $X^* \cup V_0^*$. Also, $V_0^* \cap X^* = \emptyset$ by definition of X^* in (4) – see Subsection 8.5. Altogether, this implies the remainder of (iii).

To prove the first part of (iv), note that (iii) and Lemma 33(iv) applied with $X' := V \setminus V_{Exit}$ and $Y' := V^+ \setminus V_{Entry}^+$ together imply that $(V \setminus V_{Exit}, V^+ \setminus V_{Entry}^+)_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular. The second part of (iv) can be proved similarly. It remains to prove (v). If V is nearly 4-good then (v) follows from (ii) and (iv) and Lemma 12. If $V \in \mathcal{Z}_L^- \cup \mathcal{Z}_R^-$ then (v) is trivial since $V_{Exit} = V$ and $V_{Entry}^+ = V^+$ by the second condition in (b''). In all other cases the third condition of (b'') implies that $V_{Exit} = V_{exit}$ and so $V_{Entry}^+ = V_{entry}^+$ by (ii) and the fact that $|V_{Exit}| = |V_{entry}^+|$ by Lemma 33(iii). Thus in these cases (v) follows from Lemma 33(iii). \square

Let \mathcal{C} denote a spanning subdigraph of G whose edge set consists of \mathcal{E} together with a perfect matching from $V \setminus V_{Exit}$ to $V^+ \setminus V_{Entry}^+$ for every cluster V . Then \mathcal{C} is a 1-factor of G . We will show that by choosing a different perfect matching from $V \setminus V_{Exit}$ to $V^+ \setminus V_{Entry}^+$ for some clusters V if necessary, we can ensure that \mathcal{C} consists of only one cycle, i.e. that \mathcal{C} is a Hamilton cycle of G . First we show that if U is 4-good then we can merge most vertices of U^- , U and U^+ into a single cycle of \mathcal{C} .

Lemma 37. *We can choose the perfect matchings from $V \setminus V_{Exit}$ to $V^+ \setminus V_{Entry}^+$ (for all clusters V) so that the following holds for every cluster U .*

- (i) *If U is nearly 4-good then all vertices in $U \setminus (U_{Exit} \cap U_{Entry})$ lie on a common cycle C_U of \mathcal{C} .*
- (ii) *If U is 4-good then $C_{U^-} = C_U = C_{U^+}$.*

Proof. Recall that if U is nearly 4-good then $|U_{Exit}|, |U_{Entry}| \leq 4\gamma^{1/2}m$ by Lemma 36(iii). Then it is clear that (i) implies (ii), so it suffices to prove (i). We will consider each nearly 4-good cluster U in turn and show that we can change the perfect matchings from $U^- \setminus U_{Exit}^-$ to $U \setminus U_{Entry}$ and from $U \setminus U_{Exit}$ to $U^+ \setminus U_{Entry}^+$ to ensure that U satisfies the conclusions of the lemma, and moreover, every V satisfying the conclusions continues to satisfy them. First we choose the perfect matching from $U^- \setminus U_{Exit}^-$ to $U \setminus U_{Entry}$ to achieve the following.

- (1) All vertices which were on a common cycle in \mathcal{C} are still on a common cycle.
- (2) All vertices in $(U^- \setminus U_{Exit}^-) \cup (U \setminus U_{Entry})$ lie on a common cycle in \mathcal{C} .

Since $(U^- \setminus U_{Exit}^-, U \setminus U_{Entry})_{G'}$ is $(\sqrt{\varepsilon}, d^2)$ -super-regular by Lemma 36(iv), this can be achieved by the same argument used to prove statement (†) at the end of Section 7. Next we apply the same argument to merge all the cycles in (the new) \mathcal{C} meeting $U^+ \setminus U_{Entry}^+$ into a single cycle, which then also contains all the vertices in $U \setminus U_{Exit}$. Since $|U_{Exit}|, |U_{Entry}| \leq 4\gamma^{1/2}m$ by Lemma 36(iii), we have that $U_{Exit} \cup U_{Entry} \neq U$. Thus the 1-factor \mathcal{C} obtained in this way satisfies (1) and (i) for the cluster U . Continuing in this way for all 4-good clusters and their F -neighbours yields a 1-factor \mathcal{C} as required in (i). \square

We will now show that any 1-factor \mathcal{C} as in Lemma 37 must consist of a single cycle (and thus must be a Hamilton cycle of G).

Lemma 38. *Every 1-factor \mathcal{C} of G as in Lemma 37 satisfies the following conditions.*

- (i) *For every cycle C of \mathcal{C} there exists a 4-good cluster $U \in L \cup R$ such that $C = C_U$, i.e. C contains all vertices in $U \setminus (U_{Exit} \cap U_{Entry})$.*
- (ii) *There is one cycle \mathcal{C}_L in \mathcal{C} which contains $U \setminus (U_{Exit} \cap U_{Entry})$ for every 4-good cluster $U \in L$. Similarly, there is some cycle \mathcal{C}_R in \mathcal{C} which contains $U \setminus (U_{Exit} \cap U_{Entry})$ for every 4-good cluster $U \in R$.*
- (iii) *$\mathcal{C} = \mathcal{C}_L = \mathcal{C}_R$ (and thus \mathcal{C} is a Hamilton cycle of G).*

Proof. First consider the case when C contains at least one edge in \mathcal{E} , and let P be the longest subpath of C which only consists of edges in \mathcal{E} . By Lemma 36(i) P has an endvertex x lying in a 4-excellent (and so 4-good) cluster U . But x cannot lie in both U_{Exit} and U_{Entry} by the maximality of the path. Therefore $x \in C_U$, and so $C = C_U$. Now suppose that C does not contain any edges of \mathcal{E} . This means that there is some cycle $C' \in F$ such that C ‘winds around’ C' , i.e. it only uses clusters in C' and in each step moves from V to V^+ for some $V \in C'$. We claim that C' cannot be bad. Otherwise, it would contain a cluster $V \in \mathcal{Z}_L \cup \mathcal{Z}_R$. But then the second part of (b'') implies that $V_{Entry} = V$, so C cannot ‘wind around’ C' . (The purpose of the walks W_L^{bad} and W_R^{bad} was to exclude this possibility.) Thus C' is not bad, so contains a 4-good cluster $U \in L \cup R$, which C must meet in at least one vertex, u say. But $u \notin U_{Exit} \cup U_{Entry}$ (otherwise one edge at u on C would lie in \mathcal{E}). Now Lemma 37(i) implies that C contains all vertices in $U \setminus (U_{Exit} \cap U_{Entry})$, as required.

To prove the first part of (ii), consider the walk W_L^{good} which connected all 4-good clusters in L . Let $W_L^{good} = X_1 C_1 X_1^- X_2 C_2 X_2^- \dots X_t C_t X_t^- X_{t+1}$, where $X_1 = X_{t+1} = V^*$. Then each 4-good cluster in L appears at least once in X_1, \dots, X_{t+1} , and W_L^{good} only uses nearly 4-good clusters. Let $x_i^- x_{i+1}$ be the edge in \mathcal{E} that we have chosen for the edge $X_i^- X_{i+1}$ on W_L^{good} . As neither x_i^- nor x_{i+1} was a prescribed endvertex for $X_i^- X_{i+1}$, we have $x_i^- \in (X_i^-)_{Exit} \setminus (X_i^-)_{Entry}$ and $x_{i+1} \in (X_{i+1})_{Entry} \setminus (X_{i+1})_{Exit}$. Thus $x_i^- \notin (X_i^-)_{Entry}$ and $x_{i+1} \notin (X_{i+1})_{Exit}$ by Lemma 36(iii). So Lemma 37(ii) implies that for each $i = 2, \dots, t$ the vertices x_i^- and x_{i+1} lie on the same cycle of \mathcal{C} . Trivially, x_i^- and x_{i+1} also lie on the same cycle for each $i = 1, \dots, t$. This means that all of $x_2, \dots, x_{t+1}, x_1^-, \dots, x_t^-$ lie on the same cycle of \mathcal{C} , which we will call \mathcal{C}_L . This in turn implies that \mathcal{C}_L contains $U \setminus (U_{Exit} \cap U_{Entry})$ for every 4-good cluster $U \in L$. Indeed, $U = X_i$ for some $i = 2, \dots, t+1$ and $x_i \in U_{Entry} \setminus U_{Exit} \subseteq U \setminus (U_{Exit} \cap U_{Entry})$. As $x_i \in \mathcal{C}_L$, Lemma 37(i) implies that \mathcal{C}_L contains all vertices in $U \setminus (U_{Exit} \cap U_{Entry})$. A similar argument for W_R^{good} establishes the existence of \mathcal{C}_R .

To verify (iii), consider an exceptional vertex x of type TR (which exists since we are assuming that $|TR| > |BL|$). Let x^- and x^+ be the neighbours of x on the cycle $C \in \mathcal{C}$ which contains x . Let X be the cluster containing x^- and X' be the cluster containing x^+ . By Lemma 32, $X \in T$, $X' \in R$ and both X and X' are 5-excellent (and thus 4-good). Since $x^+ \in X'_{Entry} \setminus X'_{Exit}$ and so $x^+ \in X' \setminus (X'_{Exit} \cap X'_{Entry})$ by Lemma 36(iii), we must have $C = \mathcal{C}_R$. But on the other hand, $x^- \in X \setminus (X_{Exit} \cap X_{Entry})$ and $X^+ \in L$ is 4-good (since X is 5-excellent). Together with Lemma 37(ii) this implies that C contains $X \setminus (X_{Exit} \cap X_{Entry})$, i.e. $C = \mathcal{C}_L = \mathcal{C}_R$. Together with (i) this now implies that $C = \mathcal{C}$, as required. \square

10.2. The case when $(\star\star)$ holds. Recall that $(\star\star)$ is the case when $|\widetilde{M}| \geq |V_0|/\gamma^3$. We only consider the case when $|TR| \geq |BL|$, as the argument for the other case is similar. Let F_{RL} denote the set of all those cycles in F which avoid all the clusters in $L \cup R$ and contain more clusters from M_V^{RL} than from M_V^{LR} . Let F_{LR} denote the set of all other cycles in F which avoid all the clusters in $L \cup R$.

We divide the argument in this subsection into two cases. The main case is when $|TR| - |BL| > |F_{RL}| + |F_{LR}|$. We start by showing that we have at least $\frac{|TR| - |BL|}{10\gamma^3}$ transitions from \widetilde{B} to \widetilde{L} . Note that $|\widetilde{M}_V| \geq |\widetilde{M}|/2 \geq |V_0|/(2\gamma^3)$. If $|\widetilde{M}_V^{RL}| \geq |V_0|/(4\gamma^3)$ then, since $|TR| - |BL| \leq |V_0|$, we can use vertices in $\widetilde{M}_V^{RL} \cup \widetilde{M}_H^{RL}$ as in Subsection 8.5 to obtain the required transitions. On the other hand, if $|\widetilde{M}_V^{RL}| \leq |V_0|/(4\gamma^3)$ then $|\widetilde{M}_V^{LR}| \geq |V_0|/(4\gamma^3)$. Applying Lemma 34(i) and recalling $|V_0| \leq d^{1/4}n \ll \gamma^4 n$ we obtain

$$|\text{Match}_{BL}| \geq \min\{|\widetilde{M}_V^{LR}|/2, \gamma^4 n\} - |\widetilde{M}_V^{RL}| - |V_0| \geq \frac{|V_0|}{8\gamma^3} - |\widetilde{M}_V^{RL}| - |V_0| \geq \frac{|TR| - |BL|}{10\gamma^3} - |\widetilde{M}_V^{RL}|.$$

Thus the pseudo-matching Match_{BL} and the vertices in $\widetilde{M}_V^{RL} \cup \widetilde{M}_H^{RL}$ together give at least $\frac{|TR| - |BL|}{10\gamma^3}$ transitions from \widetilde{B} to \widetilde{L} .

We claim we can choose a sub-pseudo-matching Match'_{BL} of Match_{BL} and a set $\text{Entry}_{RL} \subseteq \widetilde{M}_V^{RL}$ with the following properties.

- (i) $|\text{Match}'_{BL}| + |\text{Entry}_{RL}| = |TR| - |BL| + |F_{LR}|$,
- (ii) No cluster contains more than $\gamma m/2$ endpoints of Match'_{BL} or more than $\gamma m/2$ vertices in Entry_{RL} .
- (iii) Every cycle in F_{RL} contains at least one vertex of Entry_{RL} .

To see this, we first choose a vertex in M_V^{RL} on every cycle in F_{RL} to include in Entry_{RL} , which is possible since $|TR| - |BL| \geq |F_{RL}|$. Next we arbitrarily discard one edge from each 2-edge path in Match_{BL} to obtain a matching, and then consider a random submatching in which every edge is retained with probability $\gamma/4$. As in Case 1 of the proof of Lemma 34, with high probability we obtain a submatching of size at least $\frac{2}{9}|\text{Match}_{BL}|$ with at most $\gamma m/2$ endpoints in any cluster. We also arbitrarily choose $\gamma m/2$ vertices in each cluster of M_V^{RL} . Then we still have at least $\gamma^{-1}(|TR| - |BL|)$ transitions. Since $|TR| - |BL| \geq |F_{LR}|$, we can arbitrarily choose some of these transitions so that $|\text{Match}'_{BL}| + |\text{Entry}_{RL}| = |TR| - |BL| + |F_{LR}|$.

Note that there are no clusters which are M^{RL} -full or full with respect to Match'_{BL} . In particular, every cluster is 4-good. Next we choose twins as in Subsection 8.5 so that the properties in Lemma 33(ii)–(iv) hold. Thus we obtain sets Exit_{BL} , Entry_{BL} , $\text{Exit}_{BL}^{\text{twin}}$, $\text{Entry}_{BL}^{\text{twin}}$, Entry_{RL} , $\text{Entry}_{RL}^{\text{twin}}$ as before.

We now proceed similarly as in Subsection 10.1, forming a walk W that incorporates all the exceptional vertices and uses $|TR| - |BL|$ transitions, ending in some 4-excellent cluster $V^* \in L$. Since all clusters are 4-good, the bad cycles are precisely those in $F_{LR} \cup F_{RL}$. Now we cannot construct the walks W_L^{bad} and W_R^{bad} as before, since the bad cycles avoid $L \cup R$. Instead, we enlarge W by including a walk W_{LR} which ‘connects’ all the cycles in F_{LR} . Suppose that C_1, \dots, C_t are the cycles in F_{LR} and choose a cluster $V_i \in M_H^{LR}$ on each C_i . Lemma 28(i) implies that, in R_{G^ν} , each V_i^+ has many (at least $\beta k/4$) 4-excellent inneighbours in T , while each V_i has many 4-excellent outneighbours in R . We pick 4-excellent inneighbours $X_i \in T$ of V_i^+ and 4-excellent outneighbours $Y_i \in R$ of V_i for each i . Now we construct W_{LR} as follows. We start at $V^* \in L$, follow a useful shifted walk to $X_1^+ \in L$, then the path in F from X_1^+ to $X_1 \in T$ and then use the edge $X_1 V_1^+$. Next we wind around C_1 to V_1 , use the edge $V_1 Y_1$ and follow a useful shifted walk from Y_1 to one of the $|F_{LR}|$ transitions from \widetilde{B} to \widetilde{L} that we have not yet used to move back to L . We continue in this way until we have ‘connected’ all the C_i . Finally, we close W_{LR} by following a useful shifted walk back to V^* .

As in Subsection 10.1, we fix the edges \mathcal{E} and choose matchings from $V \setminus V_{\text{Exit}}$ to $V^+ \setminus V_{\text{Entry}}^+$ for each cluster V to obtain a 1-factor \mathcal{C} . Note that by construction every vertex outside of V_0 is incident to at most one edge of \mathcal{E} , so $V_{\text{Exit}} \cap V_{\text{Entry}} = \emptyset$ for each cluster V . Lemmas 36 and 37 still hold, but instead of Lemma 38(i) we now only have that for every cycle C of \mathcal{C} there exists a cluster U (which is automatically 4-good) such that C contains all the vertices in U . We then deduce that \mathcal{C} has a cycle \mathcal{C}_L containing all vertices in clusters of L and a cycle \mathcal{C}_R containing all vertices in clusters of R . Moreover, since we use at least one transition from \widetilde{B} to \widetilde{L} we have $\mathcal{C}_L = \mathcal{C}_R := \mathcal{C}'$. Lemma 37 now implies that for every cycle D in F there is a cycle C in \mathcal{C} such that C contains all vertices belonging to clusters in D . In particular, \mathcal{C}' contains all vertices belonging to clusters which lie on an F -cycle that intersects $L \cup R$.

Moreover, if $C \neq \mathcal{C}'$ is another cycle in \mathcal{C} , then there must be a cycle D in F such that D only consists of clusters from M_V and such that C contains all vertices in U for all clusters U on D . If $D \in F_{RL}$ then our choice of Entry_{RL} implies that some such cluster U on D contains a vertex $x \in \text{Entry}_{RL}$. The inneighbour y of x in \mathcal{C} lies in some cluster $Y \in B$ and so Y^+ in R . But \mathcal{C}' contains all vertices belonging to clusters that lie on an F -cycle which intersects R . So \mathcal{C}' contains all vertices in Y , and thus contains x . This shows that \mathcal{C}' contains all those vertices which belong to clusters lying on cycles from F_{RL} . On the other hand, the walk W_{LR} ensures that \mathcal{C}' also contains all those vertices which belong to clusters lying on cycles from F_{LR} . Altogether this shows that $\mathcal{C}' = \mathcal{C}$ is a Hamilton cycle, as required.

It remains to consider the case when $0 \leq |TR| - |BL| \leq |F_{RL}| + |F_{LR}|$. We claim that there are at least $m/4$ transitions from \tilde{T} to \tilde{R} and at least $m/4$ transitions from \tilde{B} to \tilde{L} . If $M_V^{RL} \neq \emptyset$, then we can use the vertices in $\tilde{M}_V^{RL} \cup \tilde{M}_H^{RL}$ to get at least m transitions from \tilde{B} to \tilde{L} . On the other hand, if $M_V^{RL} = \emptyset$ then $|\tilde{M}_V^{LR}| \geq |\tilde{M}|/2 \geq |V_0|/(2\gamma^3)$ by $(\star\star)$, so Lemma 34(i) implies the existence of a pseudo-matching from \tilde{B} to \tilde{L} of size at least $\min\{|\tilde{M}_V^{LR}|/2, \gamma^4 n\} - |V_0| \geq \min\{|\tilde{M}_V^{LR}|/4, \gamma^4 n/2\} \geq m/4$. Similarly, if $M_V^{LR} \neq \emptyset$ then the vertices in $\tilde{M}_V^{LR} \cup \tilde{M}_H^{LR}$ give at least m transitions from \tilde{T} to \tilde{R} . On the other hand, if $M_V^{LR} = \emptyset$ then Lemma 34(ii) implies the existence of a pseudo-matching from \tilde{T} to \tilde{R} of size at least $m/4$. Thus in all cases, we have at least $m/4$ transitions in both directions. We can use these transitions to argue similarly as in the first case when $|TR| - |BL| > |F_{RL}| + |F_{LR}|$, but this time we also include a walk W_{RL} into W which ‘connects’ all the cycles in F_{RL} . Since $|TR| - |BL| \leq |F_{RL}| + |F_{LR}| \leq k \ll m$ there are more than enough transitions. Moreover, if $|F_{RL}| + |F_{LR}| = 0$, then we also make sure that W follows at least one transition from \tilde{B} to \tilde{L} (and thus at least one transition from \tilde{T} to \tilde{R}). Then we find a Hamilton cycle by the same argument as above.

10.3. The case when $|TR| = |BL|$ and (\star) holds. If $|TR| = |BL| \geq 1$ then we can use the same procedure as in Subsection 10.1, with no need to use any edges from Match_{BL} or Match_{TR} . For the remainder of the proof we consider the case when $|TR| = |BL| = 0$. In this case, our list of the vertices of V_0 has all vertices of type TL followed by all vertices of type BR , so we will need to make a transition from incorporating vertices of type TL to type BR and then another transition back from type BR to type TL , i.e. we need one transition from \tilde{T} to \tilde{R} and another one from \tilde{B} to \tilde{L} . If M_V^{LR} and M_V^{RL} are both non-empty, then a similar argument as in the second case of the previous subsection implies that there are at least $m/4$ transitions from \tilde{B} to \tilde{L} and at least $m/4$ transitions from \tilde{T} to \tilde{R} .

Thus we may suppose that at least one of M_V^{LR}, M_V^{RL} is empty. We only consider the case when $M_V^{RL} = \emptyset$ (and M_V^{LR} could be empty or non-empty), as the other case is similar. Let x_1 and x_2 be the first and last vertices of the TL list and y_1 and y_2 the first and last vertices of the BR list. Let $X_2 \in L$ be the cluster containing the outneighbour of x_2 in Match_L , $Y_1 \in B$ the cluster containing the inneighbour of y_1 in Match_B , $Y_2 \in R$ the cluster containing the outneighbour of y_2 in Match_R , and $X_1 \in T$ the cluster containing the inneighbour of x_1 in Match_T . We need to construct portions of our walk W that link X_2 to Y_1 and Y_2 to X_1 . (If for instance the TL list is empty, we take X_1 to be an arbitrary cluster in T .) We consider two subcases according to whether there is a cycle of F that contains both a cluster of L and a cluster of R .

Case 1. *There is a cycle C of F containing a cluster $X \in L$ and a cluster $Y \in R$.*

In this case we can reroute along C to construct the required transitions. Let W_1 be a shifted walk from Y_2 to Y_1^+ . This exists since $Y_2, Y_1^+ \in R$. Also, since C contains $Y \in R$ we can choose the walk W_1 to go via Y , and C will be one of the cycles traversed. Similarly we can choose a shifted walk W_2 from X_2 to X_1^+ , and we can choose W_2 to go via X , so it also traverses C . Now we construct the portions of the walk W joining x_2 to y_1 and y_2 to x_1 as follows. To join x_2 to y_1 we start at X_2 , follow W_2 until it reaches X , then follow C round to Y^- , and then switch to W_1 , which takes us to Y_1^+ , and we end by traversing a cycle of F to reach Y_1 . This is balanced with respect to all cycles of F except for C , where we have only used the portion from X to Y^- . To join y_2 to x_1 we start at Y_2 , follow W_1 until it reaches Y , then follow C round to X^- , and then switch to W_2 , which we follow to X_1^+ , then traverse a cycle of F to reach X_1 . This is balanced with respect to all cycles of F except for C , where it only uses the portion from Y to X^- . But this is exactly the missing portion from the first transition, so in combination they are balanced with respect to all cycles of F . This scenario is illustrated in Figure 5.

Case 2. *No cycle of F contains clusters from both L and R .*

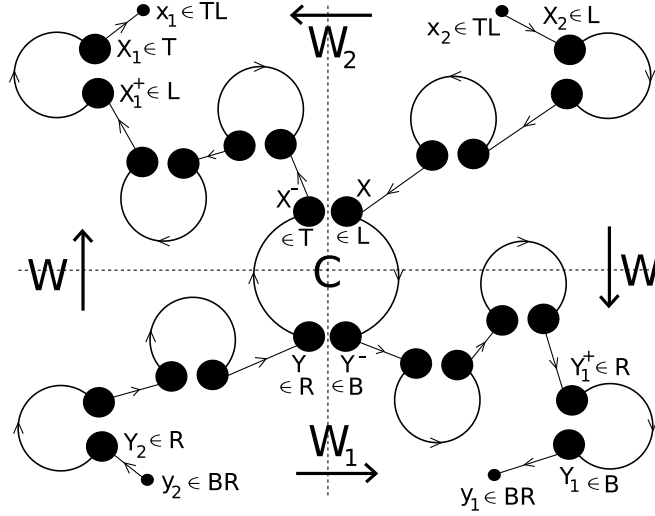


FIGURE 5. Rerouting a cycle with both left and right clusters

First we observe that in this case we have $B \subseteq R \cup M_V$ and $T \subseteq L \cup M_H$. To see the first inclusion, note that if $U \in B$ then $U^+ \in R$, so we cannot have $U \in L$ by our assumption for this case. The second inclusion is similar. Since $|\tilde{L}|, |\tilde{R}| = n/2 \pm 19\eta n$ by Lemma 27 and since $\delta(G) \geq \beta n$, every vertex in V_0 has either at least $\beta n/3$ inneighbours in \tilde{T} or at least $\beta n/3$ inneighbours in \tilde{B} (and similarly for outneighbours in \tilde{L} and \tilde{R}). So by swapping the types of the exceptional vertices between TL and BR if necessary, we may assume that each $v \in TL$ has either at least $\beta n/3$ inneighbours in \tilde{T} or at least $\beta n/3$ outneighbours in \tilde{L} (or both), and similarly for the exceptional vertices of type BR .

Recall that M_V^{RL} is empty. We consider two further subcases according to whether or not M_V^{LR} is also empty.

Case 2.1 $M_V^{LR} \neq \emptyset$.

We start by choosing an edge yy' from $\tilde{B} \cup BR$ to $\tilde{L} \cup TL$ such that $y \in \tilde{B} \setminus V_0^*$ or $y' \in \tilde{L} \setminus V_0^*$ (or both). Such an edge exists by Lemma 35(v), since $|V_0^*| = 2|V_0| \ll \beta n$. If both $y \in \tilde{B} \setminus V_0^*$ and $y' \in \tilde{L} \setminus V_0^*$, then we can use yy' for the transition from \tilde{B} to \tilde{L} . Together with suitable useful shifted walks in L and in R this will achieve the transition from y_2 to x_1 . For the transition from \tilde{T} to \tilde{R} we use one vertex in M_V^{LR} , together with a twin of this vertex in M_H^{LR} . Now we may suppose that $y \notin \tilde{B} \setminus V_0^*$ or $y' \notin \tilde{L} \setminus V_0^*$. We only consider the case when the former holds, as the other case is similar. We will still aim to use yy' for the transition from \tilde{B} to \tilde{L} , although we need to make the following adjustments according to various cases for y .

If $y \in BR$ then we relabel the BR list so that $y_2 = y$. We can then use the edge yy' (together with a suitable useful shifted walk in L) to obtain a transition from y_2 to x_1 .

Suppose next that some edge in Match_R joins an exceptional vertex $u \in BR$ to y . If u has an outneighbour $v \in \tilde{R} \setminus (V_0^* \cup \{y, y'\})$, then we replace the edge uy by uv and can now use yy' to obtain a transition from \tilde{B} to \tilde{L} . If u has no such outneighbour, then u must have at least $\beta n/3$ inneighbours in \tilde{B} (by our assumption on the exceptional vertices at the beginning of Case 2) as well as at least $\beta n/3$ outneighbours in \tilde{L} . Pick such an inneighbour $u^- \in \tilde{B} \setminus V_0^*$ and such an outneighbour $u^+ \in \tilde{L} \setminus V_0^*$. We can now use the path u^-uu^+ to obtain a transition from \tilde{B} to \tilde{L} .

Finally, suppose that some edge in Match_B joins y to an exceptional vertex $u \in BR$. If u has an inneighbour $v \in \tilde{B} \setminus (V_0^* \cup \{y, y'\})$, then we replace the edge yu by vu and can now use yy' to obtain a transition from \tilde{B} to \tilde{L} . If u has no such inneighbour, then u must have at least

$\beta n/3$ inneighbours in \tilde{T} . Pick such an inneighbour $u^- \in \tilde{T} \setminus (V_0^* \cup \{y, y'\})$ and let $u^+ \in \tilde{R}$ be the outneighbour of u in the matching Match_R . We now use yy' to obtain a transition from \tilde{B} to \tilde{L} and the path u^-uu^+ to obtain a transition from \tilde{T} to \tilde{R} .

(Note that y cannot be an endvertex of some edge in Match_T or Match_L outside V_0 , since $y \in \tilde{B} \cup BR$ and $B \subseteq R \cup M_V$.)

Case 2.2 $M_V^{LR} = \emptyset$.

In this case we have $M_V = M_H = \emptyset$. Thus $B \subseteq R$, and since $|B| = |R|$ we have $B = R$. Similarly $L = T$.

Next suppose that there are exceptional vertices $v_1 \neq v_2$ such that

$$v_1 \text{ has least } \beta n/3 \text{ inneighbours in } \tilde{T} \text{ and at least } \beta n/3 \text{ outneighbours in } \tilde{R}. \quad (v_1)$$

$$v_2 \text{ has least } \beta n/3 \text{ inneighbours in } \tilde{B} \text{ and at least } \beta n/3 \text{ outneighbours in } \tilde{L}. \quad (v_2)$$

Then we use v_1 to get a transition from \tilde{T} to \tilde{R} , and use v_2 to get a transition from \tilde{B} to \tilde{L} . Now we may suppose that we cannot find v_1 and v_2 as above. It may even be that we can find neither v_1 nor v_2 as above, in which case the following holds.

Every vertex of type TL has at least $\beta n/3$ inneighbours in \tilde{T} and at least $\beta n/3$ outneighbours in \tilde{L} . Every vertex of type BR has at least $\beta n/3$ inneighbours \tilde{B} and at least \spadesuit $\beta n/3$ outneighbours in \tilde{R} .

For the remainder of the proof we suppose that either (v_1) or \spadesuit holds, as the case (v_2) is similar to (v_1) . We consider the partition $V(G) = L' \cup R'$ where $L' := \tilde{L} \cup TL$ and $R' = \tilde{R} \cup BR$. When (v_1) holds we add v_1 to either L' or R' such that the sets obtained in this way have different size. We still denote these sets by L' and R' . The following lemma will supply the required transitions.

Lemma 39.

- (i) *When (v_1) holds there is an edge yy' from $R' \setminus \{v_1\}$ to $L' \setminus \{v_1\}$ having at least one endvertex in $(\tilde{L} \cup \tilde{R}) \setminus V_0^*$.*
- (ii) *When \spadesuit holds there are two disjoint edges xx' and yy' with $x, y' \in L'$, $x', y \in R'$ such that both edges have at least one endpoint in $(\tilde{L} \cup \tilde{R}) \setminus V_0^*$.*

Proof. Suppose first that we have $d_{(1-\beta)n/2}^+ \geq (1+\beta)n/2$. Then we have at least $(1+\beta)n/2$ vertices of outdegree at least $(1+\beta)n/2$. Since $|\tilde{L}|, |\tilde{R}| = n/2 \pm 19\eta n$ (by Lemma 27) and $|V_0^*| \ll \beta n$, we can choose vertices $x \in \tilde{L} \setminus V_0^*$ and $y \in \tilde{R} \setminus V_0^*$ with outdegree at least $(1+\beta)n/2$, and then outneighbours $x' \neq y$ in $\tilde{R} \setminus V_0^*$ of x and $y' \neq x$ in $\tilde{L} \setminus V_0^*$ of y . Then xx' and yy' are the edges required in (ii) and yy' is the edge required in (i). A similar argument applies if $d_{(1-\beta)n/2}^- \geq (1+\beta)n/2$. Therefore we can assume that $d_{(1-\beta)n/2}^+ < (1+\beta)n/2$ and $d_{(1-\beta)n/2}^- < (1+\beta)n/2$. Now our degree assumptions give $d_{(1-\beta)n/2}^+ \geq n/2$ and $d_{(1-\beta)n/2}^- \geq n/2$, so there are at least $(1+\beta)n/2$ vertices of outdegree at least $n/2$ and at least $(1+\beta)n/2$ vertices of indegree at least $n/2$. We consider cases according to the size of L' and R' .

If $|R'| > |L'|$ then we have sets $X, Y \subseteq \tilde{L} \setminus V_0^*$ with $|X|, |Y| \geq \beta n/3$ such that every vertex in X has at least 2 outneighbours in R' and every vertex in Y has at least 2 inneighbours in R' . Then we can obtain the required edges greedily: if \spadesuit holds, choose any $x \in X$, an outneighbour $x' \in R'$ of x , any $y' \in Y$ with $y' \neq x$ and any inneighbour $y \in R'$ of y' with $y \neq x'$; if (v_1) holds, then we choose $y \in R' \setminus \{v_1\}$ and an outneighbour $y' \in L' \setminus \{v_1\}$. A similar argument applies when $|L'| > |R'|$.

Finally we have the case $|L'| = |R'| = n/2$, in which case \spadesuit holds by definition of L' and R' . Then we have sets $X \subseteq \tilde{L} \setminus V_0^*$ and $Y \subseteq \tilde{R} \setminus V_0^*$ of vertices with outdegree at least $n/2$, with $|X|, |Y| \geq \beta n/3$. Note that each $x \in X$ has at least one outneighbour in R' and each $y \in Y$ has at least one outneighbour in L' . Choose some $x_0 \in X$ and an outneighbour $x'_0 \in R'$ of x_0 .

If there is any $y \in Y$, $y \neq x'_0$ with an outneighbour $y' \neq x_0$ in L' then $x_0x'_0$ and yy' are our required edges. Otherwise, we have the edge yx_0 for every $y \in Y$ with $y \neq x'_0$. So we choose some other $x \in X$ with $x \neq x_0$, an outneighbour $x' \in R'$ of x and a vertex $y \in Y \setminus \{x'_0, x'\}$, and our required edges are xx' and yx_0 . \square

Now suppose that (v_1) holds. Let yy' be the edge provided by Lemma 39(i). If $y \in \tilde{R} \setminus V_0^*$ and $y' \in \tilde{L} \setminus V_0^*$, then we can use yy' for the transition from $\tilde{B} = \tilde{R}$ to \tilde{L} . For the transition from $\tilde{T} = \tilde{L}$ to \tilde{R} we use a path $v_1^- v_1 v_1^+$ such that $v_1^- \in \tilde{L} \setminus (V_0^* \cup \{y, y'\})$ and $v_1^+ \in \tilde{R} \setminus (V_0^* \cup \{y, y'\})$. (Such a path exists since v_1 has many inneighbours in \tilde{L} and many outneighbours in \tilde{R} .) Now we may suppose that either $y \notin \tilde{R} \setminus V_0^*$ or $y' \notin \tilde{L} \setminus V_0^*$. We only consider the case when the former holds, as the other case is similar. We still aim to use yy' for the transition from \tilde{B} to \tilde{L} , although we need to make adjustments as in Case 2.1. For example, consider the case when some edge in Match_B joins y to an exceptional vertex $u \in BR$. If u has an inneighbour $v \in \tilde{B} \setminus (V_0^* \cup \{y, y'\})$, then we replace the edge yu by vu and can now use yy' to obtain a transition from \tilde{B} to \tilde{L} . If u has no such inneighbour, then u must have at least $\beta n/3$ inneighbours in $\tilde{T} = \tilde{L}$. Choose such an inneighbour $u^- \in \tilde{T} \setminus (V_0^* \cup \{y, y'\})$ and let u^+ be the outneighbour of u in Match_R . Add v_1 to the set TL, BR which contained it previously. We can now use yy' to obtain a transition from \tilde{B} to \tilde{L} and the path u^-uu^+ to obtain a transition from \tilde{T} to \tilde{R} . The other cases are similar to those in Case 2.1.

Finally, suppose that (\spadesuit) holds. Let xx', yy' be the edges provided by Lemma 39(ii). Then by changing the edges in $\text{Match}_L \cup \text{Match}_R \cup \text{Match}_T \cup \text{Match}_B$ if necessary we can ensure that $x, x', y, y' \notin V_0^*$. Now we can use xx' for the transition from \tilde{T} to \tilde{R} and yy' for the transition from \tilde{B} to \tilde{L} . This is clear if none of x, x', y, y' lies in V_0 . But if we have $x \in V_0$ (for example), then $x \in TL$, and relabelling the TL list so that $x = x_2$ we can use xx' for the transition from x_2 to y_1 . The other cases are similar.

In all of the above cases for $|TR| = |BL| = 0$ we obtain a transition from \tilde{B} to \tilde{L} and a transition from \tilde{T} to \tilde{R} . Now we can complete the proof as in Subsection 10.1. Here no cluster is full, and so every cluster is 4-good. Moreover, every vertex outside V_0 is an endvertex of at most one edge in \mathcal{E} . Thus as in Lemma 38 one can show that there are cycles $\mathcal{C}_L, \mathcal{C}_R \in \mathcal{C}$ such that \mathcal{C}_L contains all vertices belonging to clusters in L , \mathcal{C}_R contains all vertices belonging to clusters in R and every exceptional vertex lies in \mathcal{C}_L or \mathcal{C}_R . Moreover, since every cluster is 4-good and every vertex outside V_0 is an endvertex of at most one edge in \mathcal{E} , Lemma 37 now implies that for every cycle D in F there is a cycle C' in \mathcal{C} such that C' contains all vertices belonging to clusters in D . Now considering the transition from \tilde{B} to \tilde{L} (say) we see that $\mathcal{C}_L = \mathcal{C}_R$. Since (\star) implies that every cycle of F contains at least one cluster from $L \cup R$, we also have that all vertices in \tilde{M} are contained in $\mathcal{C}_L = \mathcal{C}_R$. Thus $\mathcal{C} = \mathcal{C}_L = \mathcal{C}_R$ is a Hamilton cycle of G . This completes the proof of Theorem 5.

11. A CONCLUDING REMARK

The following example demonstrates that the degree properties used in our main theorem cannot be substantially improved using our current method. Let G be a digraph with $V(G) = \{1, \dots, n\}$ such that $ij \in E(G)$ for every $1 \leq i < j \leq n$ and also for every $1 \leq j < i \leq an+1$ and $n - an \leq j < i \leq n$, for some $0 < a < 1/2$. Then G has minimum semidegree an and satisfies $d_i^+, d_i^- \geq i - 1$ for all $1 \leq i \leq n$, so if we apply the regularity lemma it is ‘indistinguishable’ from a digraph satisfying the hypotheses of Conjecture 2. However, any disjoint union of cycles in G covers at most $2an$ vertices, so the argument used in Section 6 breaks down. We remark that our argument may well still be useful in combination with a separate method for treating the case when the reduced digraph cannot be nearly covered by disjoint cycles.

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