HAMILTON DECOMPOSITIONS OF REGULAR TOURNAMENTS

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Abstract. We show that every sufficiently large regular tournament can almost completely be decomposed into edge-disjoint Hamilton cycles. More precisely, for each $\eta > 0$ every regular tournament G of sufficiently large order n contains at least $(1/2 - \eta)n$ edge-disjoint Hamilton cycles. This gives an approximate solution to a conjecture of Kelly from 1968. Our result also extends to almost regular tournaments.

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1. Introduction

A Hamilton decomposition of a graph or digraph G is a set of edge-disjoint Hamilton cycles which together cover all the edges of G. The topic has a long history but some of the main questions remain open. In 1892, Walecki showed that the edge set of the complete graph K_n on n vertices has a Hamilton decomposition if n is odd (see e.g. [2, 24] for the construction). If n is even, then n is not a factor of $\binom{n}{2}$, so clearly K_n does not have such a decomposition. Walecki's result implies that a complete digraph G on n vertices has a Hamilton decomposition if n is odd. More generally, Tillson [30] proved that a complete digraph G on n vertices has a Hamilton decomposition if and only if $n \neq 4, 6$.

A tournament is an orientation of a complete graph. We say that a tournament is *regular* if every vertex has equal in- and outdegree. Thus regular tournaments contain an odd number n of vertices and each vertex has in- and outdegree $(n-1)/2$. The following beautiful conjecture of Kelly (see e.g. [4, 7, 25]), which has attracted much attention, states that every regular tournament has a Hamilton decomposition:

Conjecture 1 (Kelly). *Every regular tournament on n vertices can be decomposed into $(n-1)/2$ edge-disjoint Hamilton cycles.*

In this paper we prove an approximate version of Kelly's conjecture.

Theorem 2. *For every $\eta > 0$ there exists an integer n_0 so that every regular tournament on $n \geq n_0$ vertices contains at least $(1/2 - \eta)n$ edge-disjoint Hamilton cycles.*

In fact, we prove the following stronger result, where we consider orientations of almost complete graphs which are almost regular. An *oriented graph* is obtained from an undirected graph by orienting its edges. So it has at most one edge between every pair of vertices, whereas a digraph may have an edge in each direction.

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Theorem 3. *For every $\eta_1 > 0$ there exist $n_0 = n_0(\eta_1)$ and $\eta_2 = \eta_2(\eta_1) > 0$ such that the following holds. Suppose that G is an oriented graph on $n \geq n_0$ vertices such that every vertex in G has in- and outdegree at least $(1/2 - \eta_2)n$. Then G contains at least $(1/2 - \eta_1)n$ edge-disjoint Hamilton cycles.*

The *minimum semidegree* $\delta^0(G)$ of an oriented graph G is the minimum of its minimum outdegree and its minimum indegree. So the minimum semidegree of a regular tournament on n vertices is $(n-1)/2$. Most of the previous partial results towards Kelly's conjecture have been obtained by giving bounds on the minimum semidegree of an oriented graph which guarantees a Hamilton cycle. This approach was first used by Jackson [16], who showed that every regular tournament on at least 5 vertices contains a Hamilton cycle and a Hamilton path which are edge-disjoint. Zhang [32] then showed that every such tournament contains two edge-disjoint Hamilton cycles. Improved bounds on the value of $\delta^0(G)$ which forces a Hamilton cycle were then found by Thomassen [28], Häggkvist [13], Häggkvist and Thomason [14] as well as Kelly, Kühn and Osthus [19]. Finally, Keevash, Kühn and Osthus [18] showed that every sufficiently large oriented graph G on n vertices with $\delta^0(G) \geq (3n-4)/8$ contains a Hamilton cycle. This bound on $\delta^0(G)$ is best possible and confirmed a conjecture of Häggkvist [13]. Note that this result implies that every sufficiently large regular tournament on n vertices contains at least $n/8$ edge-disjoint Hamilton cycles. This was the best bound so far towards Kelly's conjecture.

Kelly's conjecture has also been verified for $n \leq 9$ by Alspach (see the survey [6]). A result of Frieze and Krivelevich [12] states that Theorem 3 holds for 'quasi-random' tournaments. As indicated below, we will build on some of their ideas in the proof of Theorem 3.

It turns out that Theorem 3 can be generalized even further: any large almost regular oriented graph on n vertices whose in- and outdegrees are all a little larger than $3n/8$ can almost be decomposed into Hamilton cycles. The corresponding modifications to the proof of Theorem 3 are described in Section 6. We also discuss some further open questions in that section.

Jackson [16] also introduced the following bipartite version of Kelly's conjecture (both versions are also discussed e.g. in the Handbook article by Bondy [7]). A *bipartite tournament* is an orientation of a complete bipartite graph.

Conjecture 4 (Jackson)**.** *Every regular bipartite tournament has a Hamilton decomposition.*

An undirected version of Conjecture 4 was proved independently by Auerbach and Laskar [3], as well as Hetyei [15]. However, a bipartite version of Theorem 3 does not hold, because there are almost regular bipartite tournaments which do not even contain a single Hamilton cycle. (Consider for instance the following 'blow-up' of a 4-cycle: the vertices are split into 4 parts $A_0, \dots, A_3$ whose sizes are almost but not exactly equal, and we have all edges from A_i to A_{i+1}, with indices modulo 4.)

Kelly's conjecture has been generalized in several directions. For instance, given an oriented graph G, define its *excess* by

$$\mathrm{ex}(G) := \sum_{v \in V(G)} \max\{d^+(v) - d^-(v), 0\},$$

where $d^+(v)$ denotes the number of outneighbours of the vertex v, and $d^-(v)$ the number of its inneighbours. Pullman (see e.g. Conjecture 8.25 in [7]) conjectured that if G is an oriented graph such that $d^+(v) + d^-(v) = d$ for all vertices v of G, where d is odd, then G has a decomposition into $\mathrm{ex}(G)$ directed paths. To see that this would imply Kelly's conjecture, let G be the oriented graph obtained from a regular tournament by deleting a vertex. Another generalization was made by Bang-Jensen and Yeo [5], who conjectured that every k-edge-connected tournament has a decomposition into k spanning strong digraphs.

In [28], Thomassen also formulated the following weakening of Kelly's conjecture.

Conjecture 5 (Thomassen)**.** *If G is a regular tournament on $2k+1$ vertices and A is any set of at most $k-1$ edges of G, then $G - A$ has a Hamilton cycle.*

In [23], we proved a result on the existence of Hamilton cycles in 'robust expander digraphs' which implies Conjecture 5 for large tournaments (see [23] for details). [28] also contains the related conjecture that for any $\ell \geq 2$, there is an $f(\ell)$ so that every strongly $f(\ell)$-connected tournament contains ℓ edge-disjoint Hamilton cycles.

Further support for Kelly's conjecture was also provided by Thomassen [29], who showed that the edges of every regular tournament on n vertices can be covered by $12n$ Hamilton cycles. In [22] the first two authors observed that one can use Theorem 3 to reduce this to $(1/2 + o(1))n$ Hamilton cycles. A discussion of further recent results about Hamilton cycles in directed graphs can be found in the survey [22].

It seems likely that the techniques developed in this paper will also be useful in solving further problems. In fact, Christofides, Kühn and Osthus [9] used similar ideas to prove approximate versions of the following two long-standing conjectures of Nash-Williams [26, 27]:

Conjecture 6 (Nash-Williams [26])**.** *Let G be a $2d$-regular graph on at most $4d+1$ vertices, where $d \geq 1$. Then G has a Hamilton decomposition.*

Conjecture 7 (Nash-Williams [27])**.** *Let G be a graph on n vertices with minimum degree at least $n/2$. Then G contains $n/8 + o(n)$ edge-disjoint Hamilton cycles.*

(Actually, Nash-Williams initially formulated Conjecture 7 with the term $n/8$ replaced by $n/4$, but Babai found a counterexample to this.)

Another related problem was raised by Erdős (see [28]), who asked whether almost all tournaments G have at least $\delta^0(G)$ edge-disjoint Hamilton cycles. Note that an affirmative answer would not directly imply that Kelly's conjecture holds for almost all regular tournaments, which would of course be an interesting result in itself. There are also a number of corresponding questions for random undirected graphs (see e.g. [12]).

After giving an outline of the argument in the next section, we will state a directed version of the Regularity lemma and some related results in Section 3. Section 4 contains statements and proofs of several auxiliary results, mostly on (almost) 1-factors in (almost) regular oriented graphs. The proof of Theorem 3 is given in Section 5. A generalization of Theorem 3 to oriented graphs with smaller degrees is discussed in Section 6.

2. Sketch of the proof of Theorem 3

Suppose we are given a regular tournament G on n vertices and our aim is to 'almost' decompose it into Hamilton cycles. One possible approach might be the following: first remove a spanning regular oriented subgraph H whose degree γn satisfies $\gamma \ll 1$. Let G' be the remaining oriented subgraph of G. Now consider a decomposition of G' into 1-factors $F_1, \dots, F_r$ (which clearly exists). Next, try to transform each F_i into a Hamilton cycle by removing some of its edges and adding some suitable edges of H. This is of course impossible if many of the F_i consist of many cycles. However, an auxiliary result of Frieze and Krivelevich in [12] implies that we can 'almost' decompose G' so that each 1-factor F_i consists of only a few cycles.

If H were a 'quasi-random' oriented graph, then (as in [12]) one could use it to successively 'merge' the cycles of each F_i into Hamilton cycles using a 'rotation-extension' argument: delete an edge of a cycle C of F_i to obtain a path P from a to b, say. If there is an edge of H from b to another cycle C' of F_i, then extend P to include the vertices of C' (and similarly for a). Continue until there is no such edge. Then (in H) the current endvertices of the path P have many neighbours on P. One can use this together with the quasi-randomness of H to transform P into a cycle with the same vertices as P. Now repeat this, until we have merged all the cycles into a single (Hamilton) cycle. Of course, one has to be careful to maintain the quasi-randomness of H in carrying out this 'rotation-extension' process for the successive F_i (the fact that F_i contains only few cycles is important for this).

The main problem is that G need not contain such a spanning 'quasi-random' subgraph H. So instead, in Section 5.1 we use Szemerédi's regularity lemma to decompose G into quasi-random subgraphs. We then choose both our 1-factors F_i and the graph H according to the structure of this decomposition. More precisely, we apply a directed version of Szemerédi's regularity lemma to obtain a partition of the vertices of G into a bounded number of clusters V_i so that almost all of the bipartite subgraphs spanned by ordered pairs of clusters are quasi-random (see Section 3.3 for the precise statement). This then yields a reduced digraph R, whose vertices correspond to the clusters, with an edge from one cluster U to another cluster W if the edges from U to W in G form a quasi-random graph. (Note that R need not be oriented.) We view R as a weighted digraph whose edge weights are the densities of the corresponding ordered pair of clusters. We then obtain an unweighted multidigraph R_m from R as follows: given an edge e of R joining a cluster U to W, replace it with $K = K(e)$ copies of e, where K is approximately proportional to the density of the ordered pair (U, W). It is not hard to show that R_m is approximately regular (see Lemma 11). If R_m were regular, then it would have a decomposition into 1-factors, but this assumption may not be true. However, we can show that

R_m can 'almost' be decomposed into 'almost' 1-factors. In other words, there exist edge-disjoint collections $\mathcal{F}_1, \dots, \mathcal{F}_r$ of vertex-disjoint cycles in R_m such that each $\mathcal{F}_i$ covers almost all of the clusters in R_m (see Lemma 15).

Now we choose edge-disjoint oriented spanning subgraphs $C_1, \dots, C_r$ of G so that each C_i corresponds to $\mathcal{F}_i$. For this, consider an edge e of R from U to W and suppose for example that $\mathcal{F}_1$, $\mathcal{F}_2$ and $\mathcal{F}_8$ are the only $\mathcal{F}_i$ containing copies of e in R_m. Then for each edge of G from U to W in turn, we assign it to one of C_1, C_2 and C_8 with equal probability. Then with high probability, each C_i consists of bipartite quasi-random oriented graphs which together form a disjoint union of 'blown-up' cycles. Moreover, we can arrange that all the vertices have degree close to βm (here m is the cluster size and β a small parameter which does not depend on i). We now remove a small proportion of the edges from G (and thus from each C_i) to form oriented subgraphs $H_1^+, H_1^-, H_2, H_{3,i}, H_4, H_{5,i}$ of G, where $1 \leq i \leq r$. Ideally, we would like to show that each C_i can almost be decomposed into Hamilton cycles. Since the C_i are edge-disjoint, this would yield the required result.

One obvious obstacle is that the C_i need not be spanning subgraphs of G (because of the exceptional set V_0 returned by the regularity lemma and because the $\mathcal{F}_i$ are not spanning.) So in Section 5.2 we add suitable edges between C_i and the leftover vertices to form edge-disjoint oriented spanning subgraphs G_i of G where every vertex has degree close to βm. (The edges of H_1^- and H_1^+ are used in this step.) But the distribution of the edges added in this step may be somewhat 'unbalanced', with some vertices of C_i sending out or receiving too many of them. In fact, as discussed at the beginning of Section 5.4, we cannot even guarantee that G_i has a single 1-factor. We overcome this new difficulty by adding carefully chosen further edges (from H_2 this time) to each G_i which compensate the above imbalances.

Once these edges have been added, in Section 5.5 we can use the max-flow min-cut theorem to almost decompose each G_i into 1-factors $F_{i,j}$. (This is one of the points where we use the fact that the C_i consist of quasi-random graphs which form a union of blown-up cycles.) Moreover, (i) the number of cycles in each of these 1-factors is not too large and (ii) most of the cycles inherit the structure of $\mathcal{F}_i$. More precisely, (ii) means that most vertices u of C_i have the following property: let U be the cluster containing u and let U^+ be the successor of U in $\mathcal{F}_i$. Then the successor u^+ of u in $F_{i,j}$ lies in U^+.

In Section 5.6 we can use (i) and (ii) to merge the cycles of each $F_{i,j}$ into a 1-factor $F'_{i,j}$ consisting only of a bounded number of cycles – for each cycle $\mathcal{C}$ of $\mathcal{F}_i$, all the vertices of G_i which lie in clusters of $\mathcal{C}$ will lie in the same cycle of $F'_{i,j}$. We will apply a rotation-extension argument for this, where the additional edges (i.e. those not in $F_{i,j}$) come from $H_{3,i}$. Finally, in Section 5.7 we will use the fact that R_m contains many short paths to merge each $F'_{i,j}$ into a single Hamilton cycle. The additional edges will come from H_4 and $H_{5,i}$ this time.

3. Notation and the Diregularity lemma

3.1. **Notation.** Throughout this paper we omit floors and ceilings whenever this does not affect the argument. Given a graph G, we denote the degree of a vertex

$x \in V(G)$ by $d_G(x)$ and the maximum degree of G by $\Delta(G)$. Given two vertices x and y of a digraph G, we write xy for the edge directed from x to y. We denote by $N^+_G(x)$ the set of all outneighbours of x. So $N^+_G(x)$ consists of all those $y \in V(G)$ for which $xy \in E(G)$. We have an analogous definition for $N^-_G(x)$. Given a multidigraph G, we denote by $N^+_G(x)$ the *multiset* of vertices where a vertex $y \in V(G)$ appears k times in $N^+_G(x)$ if G contains precisely k edges from x to y. Again, we have an analogous definition for $N^-_G(x)$. We will write $N^+(x)$ for example, if this is unambiguous. Given a vertex x of a digraph or multidigraph G, we write $d^+_G(x) := |N^+(x)|$ for the outdegree of x, $d^-_G(x) := |N^-(x)|$ for its indegree and $d(x) := d^+(x) + d^-(x)$ for its degree. The maximum of the maximum outdegree $\Delta^+(G)$ and the maximum indegree $\Delta^-(G)$ is denoted by $\Delta^0(G)$. The *minimum semidegree* $\delta^0(G)$ of G is the minimum of its minimum outdegree $\delta^+(G)$ and its minimum indegree $\delta^-(G)$. Throughout the paper we will use $d^\pm_G(x)$, $\delta^\pm(G)$ and $N^\pm_G(x)$ as 'shorthand' notation. For example, $\delta^\pm(G) \geq \delta^\pm(H)/2$ is read as $\delta^+(G) \geq \delta^+(H)/2$ and $\delta^-(G) \geq \delta^-(H)/2$.

A *1-factor* of a multidigraph G is a collection of vertex-disjoint cycles in G which together cover all the vertices of G. Given $A, B \subseteq V(G)$, we write $e_G(A, B)$ to denote the number of edges in G with startpoint in A and endpoint in B. Similarly, if G is an undirected graph, we write $e_G(A, B)$ for the number of all edges between A and B. Given a multiset X and a set Y we define $X \cap Y$ to be the multiset where x appears as an element precisely k times in $X \cap Y$ if $x \in X$, $x \in Y$ and x appears precisely k times in X. We write $a = b \pm \varepsilon$ for $a \in [b - \varepsilon, b + \varepsilon]$.

3.2. **A Chernoff bound.** We will often use the following Chernoff bound for binomial and hypergeometric distributions (see e.g. [17, 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 $S \subseteq N$ of size $|S| = m$, pick a uniformly random $T \subseteq N$ of size $|T| = k$, then define $X = |T \cap S|$. Note that $\mathbb{E}X = km/n$.

Proposition 8. *Suppose X has binomial or hypergeometric distribution and $0 < a < 3/2$. Then $\mathbb{P}(|X - \mathbb{E}X| \geq a\mathbb{E}X) \leq 2e^{-\frac{a^2}{3}\mathbb{E}X}$.*

3.3. **The Diregularity lemma.** In the proof of Theorem 3 we will use the directed version of Szemerédi's Regularity lemma. Before we can state it we need some more notation and definitions. The *density* of an undirected bipartite graph G with vertex classes A and B is defined to be

$$d_G(A, B) := \frac{e_G(A, B)}{|A||B|}.$$

We will write $d(A, B)$ if this is unambiguous. Given any $\varepsilon, \varepsilon' > 0$, we say that G is *$[\varepsilon, \varepsilon']$-regular* if for all sets $X \subseteq A$ and $Y \subseteq B$ with $|X| \geq \varepsilon|A|$ and $|Y| \geq \varepsilon|B|$ we have $|d(A, B) - d(X, Y)| < \varepsilon'$. In the case when $\varepsilon = \varepsilon'$ we say that G is *ε-regular.*

Given $d \in [0, 1)$ we say that G is *(ε, d)-super-regular* if all sets $X \subseteq A$ and $Y \subseteq B$ with $|X| \geq \varepsilon|A|$ and $|Y| \geq \varepsilon|B|$ satisfy $d(X, Y) = d \pm \varepsilon$ and, furthermore, if $d_G(a) =$

$(d \pm \varepsilon)|B|$ for all $a \in A$ and $d_G(b) = (d \pm \varepsilon)|A|$ for all $b \in B$. Note that this is a slight variation of the standard definition.

Given disjoint vertex sets A and B in a digraph G, we write $(A, B)_G$ for the oriented bipartite subgraph of G whose vertex classes are A and B and whose edges are all the edges from A to B in G. We say $(A, B)_G$ is *$[\varepsilon, \varepsilon']$-regular and has density d'* if this holds for the underlying undirected bipartite graph of $(A, B)_G$. (Note that the ordering of the pair $(A, B)_G$ is important here.) In the case when $\varepsilon = \varepsilon'$ we say that *$(A, B)_G$ is ε-regular and has density d'*. Similarly, given $d \in [0, 1)$ we say $(A, B)_G$ is *(ε, d)-super-regular* if this holds for the underlying undirected bipartite graph.

The Diregularity lemma is a variant of the Regularity lemma for digraphs due to Alon and Shapira [1]. Its proof is similar to the undirected version. We will use the degree form of the Diregularity lemma which can be derived from the standard version in the same manner as the undirected degree form (see [21] for a sketch of the latter).

Lemma 9 (Degree form of the Diregularity lemma)**.** *For every $\varepsilon \in (0, 1)$ and every integer M' there are integers M and n_0 such that if G is a digraph on $n \geq n_0$ vertices and $d \in [0, 1]$ is any real number, then there is a partition of the vertex set of G into $V_0, V_1, \dots, V_L$ and a spanning subdigraph G' of G such that the following holds:*

- *$M' \leq L \leq M$,*
- *$|V_0| \leq \varepsilon n$,*
- *$|V_1| = \cdots = |V_L| =: m$,*
- *$d^{\pm}_{G'}(x) > d^{\pm}_G(x) - (d + \varepsilon)n$ for all vertices $x \in V(G)$,*
- *for all $i = 1, \dots, L$ the digraph $G'[V_i]$ is empty,*
- *for all $1 \leq i, j \leq L$ with $i \neq j$ the pair $(V_i, V_j)_{G'}$ is ε-regular and has density either 0 or at least d.*

We call $V_1, \dots, V_L$ *clusters*, V_0 the *exceptional set* and the vertices in V_0 *exceptional vertices*. We refer to G' as the *pure digraph*. The last condition of the lemma says that all pairs of clusters are ε-regular in both directions (but possibly with different densities). The *reduced digraph R of G with parameters ε, d and M'* is the digraph whose vertices are $V_1, \dots, V_L$ and in which V_iV_j is an edge precisely when $(V_i, V_j)_{G'}$ is ε-regular and has density at least d.

The next result shows that we can partition the set of edges of an ε-(super)-regular pair into edge-disjoint subgraphs such that each of them is still (super)-regular.

Lemma 10. *Let $0 < \varepsilon \ll d_0 \ll 1$ and suppose $K \geq 1$. Then there exists an integer $m_0 = m_0(\varepsilon, d_0, K)$ such that for all $d \geq d_0$ the following holds.*

(i) *Suppose that $G = (A, B)$ is an ε-regular pair of density d where $|A| = |B| = m \geq m_0$. Then there are $\lfloor K \rfloor$ edge-disjoint spanning subgraphs $S_1, \dots, S_{\lfloor K \rfloor}$ of G such that each S_i is $[\varepsilon, 4\varepsilon/K]$-regular of density $(d \pm 2\varepsilon)/K$.*

(ii) *If $K = 2$ and $G = (A, B)$ is (ε, d)-super-regular with $|A| = |B| = m \geq m_0$. then there are two edge-disjoint spanning subgraphs S_1 and S_2 of G such that each S_i is $(2\varepsilon, d/2)$-super-regular.*

Proof. We first prove (i). Suppose we have chosen m_0 sufficiently large. Initially set $E(S_i) = \emptyset$ for each $i = 1, \dots, \lfloor K \rfloor$. We consider each edge of G in turn and add it to each $E(S_i)$ with probability $1/K$, independently of all other edges of G. So the probability that xy is added to none of the S_i is $1 - \lfloor K \rfloor/K$. Moreover, $\mathbb{E}(e(S_i)) = e(G)/K = dm^2/K$.

Given $X \subseteq A$ and $Y \subseteq B$ with $|X|, |Y| \geq \varepsilon m$ we have that $|d_G(X,Y) - d| < \varepsilon$. Thus

$$\frac{1}{K}(d-\varepsilon)|X||Y| < \mathbb{E}(e_{S_i}(X,Y)) < \frac{1}{K}(d+\varepsilon)|X||Y|$$

for each i. Proposition 8 for the binomial distribution implies that with high probability $(d-2\varepsilon)|X||Y|/K < e_{S_i}(X,Y) < (d+2\varepsilon)|X||Y|/K$ for each $i \leq \lfloor K \rfloor$ and every $X \subseteq A$ and $Y \subseteq B$ with $|X|, |Y| \geq \varepsilon m$. Such S_i are as required in (i).

The proof of (ii) is similar. Indeed, as in (i) one can show that with high probability any $X \subseteq A$ and $Y \subseteq B$ with $|X|, |Y| \geq \varepsilon m$ satisfy $d_{S_i}(X,Y) = d/2 \pm 2\varepsilon$ (for $i = 1, 2$). Moreover, each vertex $a \in A$ satisfies $\mathbb{E}(d_{S_i}(a)) = d_G(a)/2 = (d \pm \varepsilon)m/2$ (for $i = 1, 2$) and similarly for the vertices in B. So again Proposition 8 for the binomial distribution implies that with high probability $d_{S_i}(a) = (d/2 \pm 2\varepsilon)m$ for all $a \in A$ and $d_{S_i}(b) = (d/2 \pm 2\varepsilon)m$ for all $b \in B$. Altogether this shows that with high probability both S_1 and S_2 are $(2\varepsilon, d/2)$-super-regular. □

Suppose $0 < 1/M' \ll \varepsilon \ll \beta \ll d \ll 1$ and let G be a digraph. Let R and G' denote the reduced digraph and pure digraph respectively, obtained by applying Lemma 9 to G with parameters ε, d and M'. For each edge V_iV_j of R we write $d_{i,j}$ for the density of $(V_i, V_j)_{G'}$. (So $d_{i,j} \geq d$.) The *reduced multidigraph* R_m of G with parameters ε, β, d and M' is obtained from R by setting $V(R_m) := V(R)$ and adding $\lfloor d_{i,j}/\beta \rfloor$ directed edges from V_i to V_j whenever $V_iV_j \in E(R)$.

We will always consider the reduced multidigraph R_m of a digraph G whose order is sufficiently large in order to apply Lemma 10 to any pair $(V_i, V_j)_{G'}$ of clusters with $V_iV_j \in E(R)$. Let $K := d_{i,j}/\beta$ and $S_{i,j,1}, \dots, S_{i,j,\lfloor K \rfloor}$ be the spanning subgraphs of $(V_i, V_j)_{G'}$ obtained from Lemma 10. (So each $S_{i,j,k}$ is ε-regular of density $\beta \pm \varepsilon$.) Let $(V_iV_j)_1, \dots, (V_iV_j)_{\lfloor K \rfloor}$ denote the directed edges from V_i to V_j in R_m. We associate each $(V_iV_j)_k$ with the edges in $S_{i,j,k}$.

Lemma 11. *Let $0 < 1/M' \ll \varepsilon \ll \beta \ll d \ll c_1 \leq c_2 < 1$ and let G be a digraph of sufficiently large order n with $\delta^0(G) \geq c_1 n$ and $\Delta^0(G) \leq c_2 n$. Apply Lemma 9 with parameters ε, d and M' to obtain a pure digraph G' and a reduced digraph R of G. Let R_m denote the reduced multidigraph of G with parameters ε, β, d and M'. Then*

$$\delta^0(R_m) > (c_1 - 3d)\frac{|R_m|}{\beta} \text{ and } \Delta^0(R_m) < (c_2 + 2\varepsilon)\frac{|R_m|}{\beta}.$$

Note the corresponding upper bound would not hold if we considered R instead of R_m here.

Proof. Given any $V_i, V_j \in V(R)$, let $d_{i,j}$ denote the density of $(V_i, V_j)_{G'}$. Then

$$(1) \qquad (c_1 - 2d)|R| \leq \frac{(c_1 - 2d)nm}{m^2} \leq \frac{\sum_{v \in V_i}\left(d^+_{G'}(v) - |V_0|\right)}{m^2} \leq \sum_{V_j \in V(R)} d_{i,j}$$

by Lemma 9. Thus

$$d^+_{R_m}(V_i) = \sum_{V_j \in V(R_m)} \left\lfloor \frac{d_{i,j}}{\beta} \right\rfloor \geq \frac{1}{\beta} \sum_{V_j \in V(R)} d_{i,j} - |R_m| \overset{(1)}{\geq} (c_1 - 2d - \beta)\frac{|R_m|}{\beta}$$
$$> (c_1 - 3d)\frac{|R_m|}{\beta}.$$

So indeed $\delta^+(R_m) > (c_1 - 3d)|R_m|/\beta$. Similar arguments can be used to show that $\delta^-(R_m) > (c_1 - 3d)|R_m|/\beta$ and $\Delta^0(R_m) < (c_2 + 2\varepsilon)|R_m|/\beta$. $\square$

We will also need the well-known fact that for any cycle C of the reduced multigraph R_m we can delete a small number of vertices from the clusters in C in order to ensure that each edge of C corresponds to a super-regular pair. We include a proof for completeness.

Lemma 12. *Let $C = V_{j_1} \dots V_{j_s}$ be a cycle in the reduced multigraph R_m as in Lemma 11. For each $t = 1, \dots, s$ let $(V_{j_t} V_{j_{t+1}})_{k_t}$ denote the edge of C which joins V_{j_t} to $V_{j_{t+1}}$ (where $V_{j_{s+1}} := V_{j_1}$). Then we can choose subclusters $V'_{j_t} \subseteq V_{j_t}$ of size $m' := (1 - 4\varepsilon)m$ such that $(V'_{j_t}, V'_{j_{t+1}})_{S_{j_t, j_{t+1}, k_t}}$ is $(10\varepsilon, \beta)$-super-regular (for each $t = 1, \dots, s$).*

Proof. Recall that for each $t = 1, \dots, s$ the digraph S_{j_t, j_{t+1}, k_t} corresponding to the edge $(V_{j_t} V_{j_{t+1}})_{k_t}$ of C is ε-regular and has density $\beta \pm \varepsilon$. So V_{j_t} contains at most $2\varepsilon m$ vertices whose outdegree in S_{j_t, j_{t+1}, k_t} is either at most $(\beta - 2\varepsilon)m$ or at least $(\beta + 2\varepsilon)m$. Similarly, there are at most $2\varepsilon m$ vertices in V_{j_t} whose indegree in $S_{j_{t-1}, j_t, k_{t-1}}$ is either at most $(\beta - 2\varepsilon)m$ or at least $(\beta + 2\varepsilon)m$. Let V'_{j_t} be a set of size m' obtained from V_{j_t} by deleting all these vertices (and some additional vertices if necessary). It is easy to check that $V'_{j_1}, \dots, V'_{j_t}$ are subclusters as required. $\square$

Finally, we will use the following crude version of the fact that every $[\varepsilon, \varepsilon']$-regular pair contains a subgraph of given maximum degree Δ whose average degree is close to Δ.

Lemma 13. *Suppose that $0 < 1/n \ll \varepsilon', \varepsilon \ll d_0 \leq d_1 \ll 1$ and that (A, B) is an $[\varepsilon, \varepsilon']$-regular pair of density d_1 with n vertices in each class. Then (A, B) contains a subgraph H whose maximum degree is at most $d_0 n$ and whose average degree is at least $d_0 n/8$.*

Proof. Let $A'' \subseteq A$ be the set of vertices of degree at least $2d_1 n$ and define B'' similarly. Then $|A''|, |B''| \leq \varepsilon n$. Let $A' := A \setminus A''$ and $B' := B \setminus B''$. Then (A', B') is still $[2\varepsilon, 2\varepsilon']$-regular of density at least $d_1/2$. Now consider a spanning subgraph H of (A', B') which is obtained from (A', B') by including each edge with probability $d_0/3d_1$. So the expected degree of every vertex is at most $2d_0 n/3$ and the expected number of edges of H is at least $d_0(n - \varepsilon n)^2/6$. Now apply the Chernoff bound on the binomial distribution in Proposition 8 to each of the vertex degrees and to the total number of edges in H to see that with high probability H has the desired properties. $\square$

4. Useful results

4.1. 1-factors in multidigraphs. Our main aim in this subsection is to show that the reduced multidigraph R_m contains a collection of 'almost' 1-factors which together cover almost all the edges of R_m (see Lemma 15). To prove this we will need the following result which implies R_m contains many edges between any two sufficiently large sets. The second part of the lemma will be used in Section 4.5.

Lemma 14. *Let $0 < 1/n \ll 1/M' \ll \varepsilon \ll \beta \ll \eta \ll d \ll c, d' \ll 1$. Suppose that G is an oriented graph of order n with $\delta^0(G) \geq (1/2 - \eta)n$. Let R and R_m denote the reduced digraph and the reduced multidigraph of G obtained by applying Lemma 9 (with parameters ε, d, M' and $\varepsilon, \beta, d, M'$ respectively). Let $L := |R| = |R_m|$. Then the following properties hold.*

- (i) *Let $X \subseteq V(R_m)$ be such that $\delta^0(R_m[X]) \geq (1/2 - c)|X|/\beta$. Then for all (not necessarily disjoint) subsets A and B of X of size at least $(1/2 - c)|X|$ there are at least $|X|^2/(60\beta)$ directed edges from A to B in R_m.*
- (ii) *Let R' denote the spanning subdigraph of R obtained by deleting all edges which correspond to pairs of density at most d' (in the pure digraph G'). Then $\delta^0(R') \geq (1/2 - 2d')L$ and for all (not necessarily disjoint) subsets A and B of $V(R')$ of size at least $(1/2 - c)L$ there are at least $L^2/60$ directed edges from A to B in R'.*

Proof. We first prove (i). Recall that for every edge V_iV_j of R there are precisely $\lfloor d_{i,j}/\beta \rfloor$ edges from V_i to V_j in R_m, where $d_{i,j}$ denotes the density of $(V_i, V_j)_{G'}$. But $d_{i,j} + d_{j,i} \leq 1$ since G is oriented and so R_m contains at most $1/\beta$ edges between V_i and V_j (here we count the edges in both directions).

By deleting vertices from A and B if necessary we may assume that $|A| = |B| = (1/2 - c)|X|$. We will distinguish two cases. Suppose first that $|A \cap B| > |X|/5$ and let $Y := A \cap B$. Define $\overline{Y} := X \backslash Y$ and $\overline{A \cup B} := X \backslash (A \cup B)$. Then

$$\begin{aligned} 2e(A, B) &\geq 2e(Y) = \sum_{V \in Y} d_{R_m[X]}(V) - e(Y, \overline{Y}) - e(\overline{Y}, Y) \\ &\geq |Y|(1 - 2c)|X|/\beta - |Y|(|X| - |Y|)/\beta = |Y|(|Y| - 2c|X|)/\beta \geq |X|^2/(30\beta). \end{aligned}$$

So suppose next that $|A \cap B| \leq |X|/5$. Then $|\overline{A \cup B}| \leq |X| - |A| - |B| + |A \cap B| \leq (1/5 + 2c)|X|$. Therefore,

$$\begin{aligned} e(A, B) &\geq \sum_{V \in A} d^+_{R_m[X]}(V) - e(A, \overline{A \cup B}) - e(A) \\ &\geq |A|(1/2 - c)|X|/\beta - |A||\overline{A \cup B}|/\beta - |A|^2/(2\beta) \\ &\geq |A|[(1/2 - c) - (1/5 + 2c) - (1/2 - c)/2]|X|/\beta \geq |X|^2/(60\beta), \end{aligned}$$

as required.

To prove (ii) we consider the weighted digraph R'_w obtained from R' by giving each edge V_iV_j of R' weight $d_{i,j}$. Given a cluster V_i, we write $w^+(V_i)$ for the sum of the weights of all edges sent out by V_i in R'_w. We define $w^-(V_i)$ similarly and write $w^0(R'_w)$ for the minimum of $\min\{w^+(V_i), w^-(V_i)\}$ over all clusters V_i. Note that $\delta^0(R') \geq w^0(R'_w)$. Moreover, Lemma 9 implies that $d^{\pm}_{G' \backslash V_0}(x) >$

$(1/2-2d)n$ for all $x \in V(G'\backslash V_0)$. Thus each $V_i \in V(R')$ satisfies

$$(1/2-2d)nm \leq e_{G'}(V_i, V(G')\backslash V_0) \leq m^2 w^+(V_i) + (d'm^2)L$$

and so $w^+(V_i) \geq (1/2-2d-d')L > (1/2-2d')L$. Arguing in the same way for inweights gives us $\delta^0(R') \geq w^0(R'_w) > (1/2-2d')L$. Let $A, B \subseteq V(R')$ be as in (ii). Similarly as in (i) (setting $\beta := 1$ and $X := V(R')$ in the calculations) one can show that the sum of all weights of the edges from A to B in R'_w is at least $L^2/60$. But this implies that R' contains at least $L^2/60$ edges from A to B. □

Lemma 15. *Let $0 < 1/n \ll 1/M' \ll \varepsilon \ll \beta \ll \eta \ll d \ll c \ll 1$. Suppose that G is an oriented graph of order n with $\delta^0(G) \geq (1/2-\eta)n$. Let R_m denote the reduced multidigraph of G with parameters ε, β, d and M' obtained by applying Lemma 9. Let $r := (1/2-c)|R_m|/\beta$. Then there exist edge-disjoint collections $\mathcal{F}_1, \dots, \mathcal{F}_r$ of vertex-disjoint cycles in R_m such that each $\mathcal{F}_i$ covers all but at most $c|R_m|$ of the clusters in R_m.*

Proof. Let $L := |R_m|$. Since $\Delta^0(G) \leq n - \delta^0(G) \leq (1/2+\eta)n$, Lemma 11 implies that

$$\delta^0(R_m) \geq (1/2-4d)\frac{L}{\beta} \quad \text{and} \quad \Delta^0(R_m) \leq (1/2+2\eta)\frac{L}{\beta}. \tag{2}$$

First we find a set of clusters $X \subseteq V(R)$ with the following properties:

- $|X| = cL$,
- $|N^{\pm}_{R_m}(V_i) \cap X| = (1/2 \pm 5d)\frac{cL}{\beta}$ for all $V_i \in V(R_m)$.

We obtain X by choosing a set of cL clusters uniformly at random. Then each cluster V_i satisfies

$$\mathbb{E}(|N^{\pm}_{R_m}(V_i) \cap X|) = c|N^{\pm}_{R_m}(V_i)| \overset{(2)}{=} c(1/2 \pm 4d)\frac{L}{\beta}.$$

Proposition 8 for the hypergeometric distribution now implies that with nonzero probability X satisfies our desired conditions. (Recall that $N^+_{R_m}(V_i)$ is a multiset. Formally Proposition 8 does not apply to multisets. However, for each $j = 1, \dots, 1/\beta$ we can apply Proposition 8 to the set of all those clusters which appear at least j times in $N^+_{R_m}(V_i)$, and similarly for $N^-_{R_m}(V_i)$.)

Note that

$$d^{\pm}_{R_m\backslash X}(V_i) = \left(\frac{1}{2} - \frac{c}{2} \pm 5d\right)\frac{L}{\beta}$$

for each $V_i \in V(R_m\backslash X)$. We now add a small number of *temporary edges* to $R_m\backslash X$ in order to turn it into an r'-regular multidigraph where $r' := (\frac{1}{2} - \frac{c}{2} + 5d)\frac{L}{\beta}$. We do this as follows. As long as $R_m\backslash X$ is not r'-regular there exist $V_i, V_j \in V(R_m\backslash X)$ such that V_i has outdegree less than r' and V_j has indegree less than r'. In this case we add an edge from V_i to V_j. (Note we may have $i = j$, in which case we add a loop.)

We decompose the edge set of $R_m\backslash X$ into r' 1-factors $\mathcal{F}'_1, \dots, \mathcal{F}'_{r'}$. (To see that we can do this, consider the bipartite multigraph H where both vertex classes A, B consist of a copy of $V(R_m\backslash X)$ and we have s edges between $a \in A$ and $b \in B$ if there are precisely s edges from a to b in $R_m\backslash X$, including the temporary edges. Then H

is regular and so has a perfect matching. This corresponds to a 1-factor $\mathcal{F}'_1$. Now remove the edges of $\mathcal{F}'_1$ from H and continue to find $\mathcal{F}'_2, \dots, \mathcal{F}'_{r'}$ in the same way.) Since at each cluster we added at most $20d\frac{L}{\beta}$ temporary edges, all but at most $20\sqrt{d}\frac{L}{\beta}$ of the $\mathcal{F}'_i$ contain at most $\sqrt{d}L$ temporary edges. By relabeling if necessary we may assume that $\mathcal{F}'_1, \dots, \mathcal{F}'_r$ are such 1-factors. We now remove the temporary edges from each of these 1-factors, though we still refer to the digraphs obtained in this way as $\mathcal{F}'_1, \dots, \mathcal{F}'_r$. So each $\mathcal{F}'_i$ spans $R_m \backslash X$ and consists of cycles and at most $\sqrt{d}L$ paths.

Our aim is to use the clusters in X to piece up these paths into cycles in order to obtain edge-disjoint directed subgraphs $\mathcal{F}_1, \dots, \mathcal{F}_r$ of R_m where each $\mathcal{F}_i$ is a collection of vertex-disjoint cycles and $\mathcal{F}'_i \subseteq \mathcal{F}_i$.

Let $P'_1, \dots, P'_\ell$ denote all the paths lying in one of $\mathcal{F}'_1, \dots, \mathcal{F}'_r$ (so $\ell \leq \sqrt{d}Lr \leq \sqrt{d}L^2/\beta$). Our next task is to find edge-disjoint paths and cycles $P_1, \dots, P_\ell$ of length 5 in R_m with the following properties.

(i) If P'_j consists of a single cluster $V_{j'} \in V(R)$ then P_j is a cycle consisting of 4 clusters in X as well as $V_{j'}$.
(ii) If P'_j is a path of length ≥ 1 then P_j is a path whose startpoint is the endpoint of P'_j. Similarly the endpoint of P_j is the startpoint of P'_j.
(iii) If P'_j is a path of length ≥ 1 then the internal clusters in the path P_j lie in X.
(iv) If P'_{j_1} and P'_{j_2} lie in the same $\mathcal{F}'_i$ then P_{j_1} and P_{j_2} are vertex-disjoint.

So conditions (i)–(iii) imply that $P'_j \cup P_j$ is a directed cycle for each $1 \leq j \leq \ell$. Assuming we have found such paths and cycles $P_1, \dots, P_\ell$, we define $\mathcal{F}_1, \dots, \mathcal{F}_r$ as follows. Suppose $P'_{j_1}, \dots, P'_{j_t}$ are the paths in $\mathcal{F}'_i$. Then we obtain $\mathcal{F}_i$ from $\mathcal{F}'_i$ by adding the paths and cycles $P_{j_1}, \dots, P_{j_t}$ to $\mathcal{F}'_i$. Condition (iv) ensures that the $\mathcal{F}_i$ are indeed collections of vertex-disjoint cycles.

It remains to show the existence of $P_1, \dots, P_\ell$. Suppose that for some $j \leq \ell$ we have already found $P_1, \dots, P_{j-1}$ and now need to define P_j. Consider P'_j and suppose it lies in $\mathcal{F}'_i$. Let V_a denote the startpoint of P'_j and V_b its endpoint.

We call an edge $(V_{i_1}V_{i_2})_k$ in R_m *free* if it has not been used in one of $P_1, \dots, P_{j-1}$. Let B be the set of all those clusters $V \in X$ for which at least $c|X|/\beta$ of the edges at V in $R_m[X]$ are not free. Our next aim is to show that B is small. More precisely,

$$|B| \leq d^{1/4}L.$$

To see this, note that $3(j-1) \leq 3\ell \leq 3\sqrt{d}\frac{L^2}{\beta}$ edges of $R_m[X]$ lie in one of $P_1, \dots, P_{j-1}$. Thus, $2 \cdot 3\sqrt{d}\frac{L^2}{\beta} \geq \frac{c|X|}{\beta}|B| = \frac{c^2L|B|}{\beta}$. (The extra factor of 2 comes from the fact that we may have counted edges at the vertices in B twice.) Since $c \gg d$ this implies that $|B| \leq d^{1/4}L$, as desired. We will only use clusters in $X' := X \backslash B$ when constructing P_j. Note that V_a receives at most $|B|/\beta \leq d^{1/4}L/\beta$ edges from B in R_m.

Since we added at most $20dL/\beta$ temporary edges to $R_m \backslash X$ per cluster, V_a can be the startpoint or endpoint of at most $20dL/\beta$ of the paths $P'_1, \dots, P'_{j-1}$. Thus V_a lies in at most $20dL/\beta$ of the paths and cycles $P_1, \dots, P_{j-1}$. In particular, at most $40dL/\beta$ edges at V_a in R_m are not free. We will avoid such edges when constructing P_j.

For each of $P_1,\dots,P_{j-1}$ we have used 4 clusters in X. Let $P'_{j_1},\dots,P'_{j_t}$ denote the paths which lie in $\mathcal{F}'_i$ (so $t\le\sqrt{d}L$). Thus at most $4\sqrt{d}L$ clusters in X already lie in the paths and cycles $P_{j_1},\dots,P_{j_t}$. So for P_j to satisfy (iv), the inneighbour of V_a on P_j must not be one of these clusters. Note that V_a receives at most $4\sqrt{d}L/\beta$ edges in R_m from these clusters.

Thus in total we cannot use $d^{1/4}L/\beta+40dL/\beta+4\sqrt{d}L/\beta\le 2d^{1/4}L/\beta$ of the edges which V_a receives from X in R_m. But $|N^-_{R_m}(V_a)\cap X|\ge(\frac{1}{2}-5d)cL/\beta\gg 2d^{1/4}L/\beta$ and so we can still choose a suitable cluster V_{a^-} in $N^-_{R_m}(V_a)\cap X$ which will play the role of the inneighbour of V_a on P_j. Let $(V_{a^-}V_a)_{k_5}$ denote the corresponding free edge in R_m which we will use in P_j.

A similar argument shows that we can find a cluster $V_{b^+}\ne V_{a^-}$ to play the role of the outneighbour of V_b on P_j. So $V_{b^+}\in X'$, V_{b^+} does not lie on any of $P_{j_1},\dots,P_{j_t}$ and there is a free edge $(V_bV_{b^+})_{k_1}$ in R_m.

We need to choose the outneighbour $V_{b^{++}}$ of V_{b^+} on P_j such that $V_{b^{++}}\in X'\setminus\{V_{a^-}\}$, $V_{b^{++}}$ has not been used in $P_{j_1},\dots,P_{j_t}$ and there is a free edge from V_{b^+} to $V_{b^{++}}$ in R_m. Let A_1 denote the set of all clusters in X' which satisfy these conditions. Since $V_{b^+}\in X'$ at most $c|X|/\beta$ edges at V_{b^+} in $R_m[X]$ are not free. So V_{b^+} sends out at least $(1/2-5d)\frac{|X|}{\beta}-c\frac{|X|}{\beta}-\frac{|B\cup\{V_{a^-}\}|}{\beta}\ge(1/2-2c)\frac{|X|}{\beta}$ free edges to $X'\setminus\{V_{a^-}\}$ in R_m. On the other hand, as before one can show that V_{b^+} sends at most $4\sqrt{d}L/\beta$ edges to clusters in X' which already lie in $P_{j_1},\dots,P_{j_t}$. Hence, $|A_1|\ge\beta[(1/2-2c)|X|/\beta-4\sqrt{d}L/\beta]\ge(1/2-3c)|X|$.

Similarly we need to choose the inneighbour $V_{a^{--}}$ of V_{a^-} on P_j such that $V_{a^{--}}\in X'\setminus\{V_{b^+}\}$, $V_{a^{--}}$ has not been used in $P_{j_1},\dots,P_{j_t}$ and so that R_m contains a free edge from $V_{a^{--}}$ to V_{a^-}. Let A_2 denote the set of all clusters in X' which satisfy these conditions. As before one can show that $|A_2|\ge(1/2-3c)|X|$.

Recall that $\delta^0(R_m[X])\ge(1/2-5d)|X|/\beta$ by our choice of X. Thus Lemma 14(i) implies that $R_m[X]$ contains at least $|X|^2/(60\beta)=c^2L^2/(60\beta)$ edges from A_1 to A_2. Since all but at most $5\ell\le5\sqrt{d}L^2/\beta$ edges of R_m are free, there is a free edge $(V_{b^{++}}V_{a^{--}})_{k_3}$ from A_1 to A_2. Let $(V_{b^+}V_{b^{++}})_{k_2}$ be a free edge from V_{b^+} to $V_{b^{++}}$ in R_m and let $(V_{a^{--}}V_{a^-})_{k_4}$ be a free edge from $V_{a^{--}}$ to V_{a^-} (such edges exist by definition of A_1 and A_2). We take P_j to be the directed path or cycle which consists of the edges $(V_bV_{b^+})_{k_1}$, $(V_{b^+}V_{b^{++}})_{k_2}$, $(V_{b^{++}}V_{a^{--}})_{k_3}$, $(V_{a^{--}}V_{a^-})_{k_4}$ and $(V_{a^-}V_a)_{k_5}$. □

4.2. **Spanning subgraphs of super-regular pairs.** Frieze and Krivelevich [12] showed that every (ε,β)-super-regular pair Γ contains a regular subgraph Γ' whose density is almost the same as that of Γ. The following lemma is an extension of this, where we can require Γ' to have a given degree sequence, as long as this degree sequence is almost regular.

Lemma 16. *Let $0<1/m\ll\varepsilon\ll\beta\ll\alpha'\ll\alpha\ll1$. Suppose that $\Gamma=(U,V)$ is an $(\varepsilon,\beta+\varepsilon)$-super-regular pair where $|U|=|V|=m$. Define $\tau:=(1-\alpha)\beta m$. Suppose we have a non-negative integer $x_i\le\alpha'\beta m$ associated with each $u_i\in U$ and a non-negative integer $y_i\le\alpha'\beta m$ associated with each $v_i\in V$ such that $\sum_{u_i\in U}x_i=$*

$\sum_{v_i\in V} y_i$. *Then* Γ *contains a spanning subgraph* Γ' *in which* $c_i := \tau - x_i$ *is the degree of* $u_i \in U$ *and* $d_i := \tau - y_i$ *is the degree of* $v_i \in V$.

Proof. We first obtain a directed network N from Γ by adding a source s and a sink t. We add an edge su_i of capacity c_i for each $u_i \in U$ and an edge v_it of capacity d_i for each $v_i \in V$. We give all the edges in Γ capacity 1 and direct them from U to V.

Our aim is to show that the capacity of any cut is at least $\sum_{u_i\in U} c_i = \sum_{v_i\in V} d_i$. By the max-flow min-cut theorem this would imply that N admits a flow of value $\sum_{u_i\in U} c_i$, which by construction of N implies the existence of our desired subgraph Γ'.

So consider any (s,t)-cut $(S,\bar{S})$ where $S = \{s\}\cup S_1 \cup S_2$ with $S_1 \subseteq U$ and $S_2 \subseteq V$. Let $\bar{S}_1 := U\backslash S_1$ and $\bar{S}_2 := V\backslash S_2$. The capacity of this cut is

$$\sum_{u_i\in \bar{S}_1} c_i + \sum_{v_i\in S_2} d_i + e(S_1,\bar{S}_2)$$

and so our aim is to show that

$$e(S_1,\bar{S}_2) \geq \sum_{u_i\in S_1} c_i - \sum_{v_i\in S_2} d_i. \tag{3}$$

Now

$$\sum_{u_i\in S_1} c_i - \sum_{v_i\in S_2} d_i \leq |S_1|(1-\alpha)\beta m - |S_2|(1-\alpha-\alpha')\beta m \tag{4}$$

and similarly

$$\sum_{u_i\in S_1} c_i - \sum_{v_i\in S_2} d_i = \sum_{v_i\in \bar{S}_2} d_i - \sum_{u_i\in \bar{S}_1} c_i \leq |\bar{S}_2|(1-\alpha)\beta m - |\bar{S}_1|(1-\alpha-\alpha')\beta m. \tag{5}$$

By (4) we may assume that $|S_1| \geq (1-2\alpha')|S_2|$. (Since otherwise $\sum_{u_i\in S_1} c_i - \sum_{v_i\in S_2} d_i < 0$ and thus (3) is satisfied.) Similarly by (5) we may assume that $|\bar{S}_2| \geq (1-2\alpha')|\bar{S}_1|$. Let $\alpha^* := \alpha'/\alpha$. We now consider several cases.

Case 1. $|S_1|, |\bar{S}_2| \geq \varepsilon m$ and $|S_1| \geq (1+\alpha^*)|S_2|$.
Since Γ is $(\varepsilon, \beta+\varepsilon)$-super-regular we have that

$$\begin{aligned} e(S_1,\bar{S}_2) &\geq \beta|S_1|(m-|S_2|) \geq \beta m(|S_1|-|S_2|) \\ &= \big(|S_1|(1-\alpha)\beta m - |S_2|(1-\alpha-\alpha')\beta m\big) + \alpha\beta m|S_1| - (\alpha+\alpha')\beta m|S_2| \\ &\geq |S_1|(1-\alpha)\beta m - |S_2|(1-\alpha-\alpha')\beta m. \end{aligned}$$

(The last inequality follows since $\alpha|S_1| \geq (\alpha+\alpha')|S_2|$.) Together with (4) this implies (3).

Case 2. $|S_1|, |\bar{S}_2| \geq \varepsilon m$, $|S_1| < (1+\alpha^*)|S_2|$ and $|S_2| \leq (1-\alpha^*)m$.
Again since Γ is $(\varepsilon, \beta+\varepsilon)$-super-regular we have that

$$e(S_1,\bar{S}_2) \geq \beta|S_1|(m-|S_2|) = \beta|S_1||\bar{S}_2|. \tag{6}$$

As before, to prove (3) we will show that

$$e(S_1,\bar{S}_2) \geq |S_1|(1-\alpha)\beta m - |S_2|(1-\alpha-\alpha')\beta m.$$

Thus by (6) it suffices to show that $\alpha m|S_1| - |S_1||S_2| + (1-\alpha-\alpha')m|S_2| \geq 0$. We know that $|S_2|(1-\alpha-\alpha') \geq |S_1|(1-\alpha-\alpha^*)$ since $(1+\alpha^*)|S_2| > |S_1|$. Hence, $\alpha|S_1| - |S_1|(1-\alpha^*) + |S_2|(1-\alpha-\alpha') \geq 0$. So $\alpha m|S_1| - |S_1||S_2| + (1-\alpha-\alpha')m|S_2| \geq 0$ as $|S_2| \leq (1-\alpha^*)m$. So indeed (3) is satisfied.

Case 3. $|S_1|, |\bar{S}_2| \geq \varepsilon m$, $|S_1| < (1+\alpha^*)|S_2|$ and $|S_2| > (1-\alpha^*)m$.

By (5) in order to prove (3) it suffices to show that

$$e(S_1, \bar{S}_2) \geq |\bar{S}_2|(1-\alpha)\beta m - |\bar{S}_1|(1-\alpha-\alpha')\beta m.$$

Since (6) also holds in this case, this means that it suffices to show that $\alpha|\bar{S}_2|m - |\bar{S}_1||\bar{S}_2| + (1-\alpha-\alpha')|\bar{S}_1|m \geq 0$. Since $|S_1| \geq (1-2\alpha')|S_2|$ and $|S_2| > (1-\alpha^*)m$ we have that $|S_1| > (1-\alpha)m$. Thus $\alpha|\bar{S}_2|m \geq |\bar{S}_1||\bar{S}_2|$ and so indeed (3) holds.

Case 4. $|S_1| < \varepsilon m$ and $|\bar{S}_2| \geq \varepsilon m$.

Since $|S_1| \geq (1-2\alpha')|S_2|$ we have that $|S_2| \leq 2\varepsilon m$. Hence,

$$e(S_1, \bar{S}_2) \geq \beta m|S_1| - |S_1||S_2| \geq (\beta - 2\varepsilon)m|S_1| \geq (1-\alpha)\beta m|S_1|$$

and so by (4) we see that (3) is satisfied, as desired.

Case 5. $|S_1| \geq \varepsilon m$ and $|\bar{S}_2| < \varepsilon m$.

Similarly as in Case 4 it follows that $e(S_1, \bar{S}_2) \geq (1-\alpha)\beta m|\bar{S}_2|$ and so by (5) we see that (3) is satisfied, as desired.

Note that we have considered all possible cases since we cannot have that $|S_1|, |\bar{S}_2| < \varepsilon m$. Indeed, if $|S_1|, |\bar{S}_2| < \varepsilon m$ then $|S_2| \geq (1-\varepsilon)m$ and as $|S_1| \geq (1-2\alpha')|S_2|$ this implies $|S_1| \geq (1-2\alpha')(1-\varepsilon)m$, a contradiction. □

4.3. **Special 1-factors in graphs and digraphs.** It is easy to see that every regular oriented graph G contains a 1-factor. The following result states that if G is also dense, then (i) we can guarantee a 1-factor with few cycles. Such 1-factors have the advantage that we can transform them into a Hamilton cycle by adding/deleting a comparatively small number of edges. (ii) implies that even if G contains a sparse 'bad' subgraph H, then there will be a 1-factor which does not contain 'too many' edges of H.

Lemma 17. *Let $0 < \theta_1, \theta_2, \theta_3 < 1/2$ and $\theta_1/\theta_3 \ll \theta_2$. Let G be a ρ-regular oriented graph whose order n is sufficiently large and where $\rho := \theta_3 n$. Suppose $A_1, \dots, A_{5n}$ are sets of vertices in G with $a_i := |A_i| \geq n^{1/2}$. Let H be an oriented subgraph of G such that $d^\pm_H(x) \leq \theta_1 n$ for all $x \in A_i$ (for each i). Then G has a 1-factor F such that*

- (i) *F contains at most $n/(\log n)^{1/5}$ cycles;*
- (ii) *For each i, at most $\theta_2 a_i$ edges of $H \cap F$ are incident to A_i.*

To prove this result we will use ideas similar to those used by Frieze and Krivelevich [12]. In particular, we will use the following bounds on the number of perfect matchings in a bipartite graph.

Theorem 18. *Suppose that B is a bipartite graph whose vertex classes have size n and $d_1, \dots, d_n$ are the degrees of the vertices in one of these vertex classes. Let $\mu(B)$ denote the number of perfect matchings in B. Then*

$$\mu(B) \le \prod_{k=1}^{n} (d_k!)^{1/d_k}.$$

Furthermore, if B is ρ-regular then

$$\mu(B) \ge \left(\frac{\rho}{n}\right)^n n!.$$

The upper bound in Theorem 18 was proved by Brégman [8]. The lower bound is a consequence of the Van der Waerden conjecture which was proved independently by Egorychev [10] and Falikman [11].

We will deduce (i) from the following result in [20], which in turn is similar to Lemma 2 in [12].

Lemma 19. *For all $\theta \le 1$ there exists $n_0 = n_0(\theta)$ such that the following holds. Let B be a θn-regular bipartite graph whose vertex classes U and W satisfy $|U| = |W| =: n \ge n_0$. Let M_1 be any perfect matching from U to W which is disjoint from B. Let M_2 be a perfect matching chosen uniformly at random from the set of all perfect matchings in B. Let $F = M_1 \cup M_2$ be the resulting 2-factor. Then the probability that F contains more than $n/(\log n)^{1/5}$ cycles is at most e^{-n}.*

Proof of Lemma 17. Consider the ρ-regular bipartite graph B whose vertex classes V_1, V_2 are copies of $V(G)$ and where $x \in V_1$ is joined to $y \in V_2$ if xy is a directed edge in G. Note that every perfect matching in B corresponds to a 1-factor of G and vice versa. Let $\mu(B)$ denote the number of perfect matchings of B. Then

$$\mu(B) \ge \left(\frac{\rho}{n}\right)^n n! \ge \left(\frac{\rho}{n}\right)^n \left(\frac{n}{e}\right)^n = \left(\frac{\rho}{e}\right)^n \tag{7}$$

by Theorem 18. Here we have also used Stirling's formula which implies that for sufficiently large m,

$$\left(\frac{m}{e}\right)^m \le m! \le \left(\frac{m}{e}\right)^{m+1}. \tag{8}$$

We now count the number $\mu_i(G)$ of 1-factors of G which contain more than $\theta_2 a_i$ edges of H which are incident to A_i. Note that

$$\mu_i(G) \le \binom{2a_i}{\theta_2 a_i} (\theta_1 n)^{\theta_2 a_i} (\rho!)^{(n-\theta_2 a_i)/\rho}. \tag{9}$$

Indeed, the term $\binom{2a_i}{\theta_2 a_i}(\theta_1 n)^{\theta_2 a_i}$ in (9) gives an upper bound for the number of ways we can choose $\theta_2 a_i$ edges from H which are incident to A_i such that no two of these edges have the same startpoint and no two of these edges have the same endpoint. The term $(\rho!)^{(n-\theta_2 a_i)/\rho}$ in (9) uses the upper bound in Theorem 18 to give a bound on the number of 1-factors in G containing $\theta_2 a_i$ fixed edges. Now

$$(\rho!)^{(n-\theta_2 a_i)/\rho} \overset{(8)}{\le} \left(\frac{\rho}{e}\right)^{(1+1/\rho)(n-\theta_2 a_i)} \le \left(\frac{\rho}{e}\right)^{n-\theta_2 a_i + 1/\theta_3} \tag{10}$$

since $\rho = \theta_3 n$ and

$$\left(\frac{e}{\rho}\right)^{\theta_2 a_i - 1/\theta_3} \leq \left(\frac{2e}{\theta_3 n}\right)^{\theta_2 a_i} \tag{11}$$

since $a_i \geq n^{1/2}$. Furthermore,

$$\binom{2a_i}{\theta_2 a_i} \leq \frac{(2a_i)^{\theta_2 a_i}}{(\theta_2 a_i)!} \overset{(8)}{\leq} \left(\frac{2e}{\theta_2}\right)^{\theta_2 a_i}. \tag{12}$$

So by (9) we have that

$$\begin{aligned} \mu_i(G) &\overset{(10),(12)}{\leq} \left(\frac{2e}{\theta_2}\right)^{\theta_2 a_i} (\theta_1 n)^{\theta_2 a_i} \left(\frac{\rho}{e}\right)^{n - \theta_2 a_i + 1/\theta_3} \\ &\overset{(11)}{\leq} \left(\frac{2e}{\theta_2}\theta_1 n \frac{2e}{\theta_3 n}\right)^{\theta_2 a_i} \left(\frac{\rho}{e}\right)^n \overset{(7)}{\leq} \left(\frac{4e^2\theta_1}{\theta_2\theta_3}\right)^{\theta_2 a_i} \mu(B) \ll \frac{\mu(B)}{5n} \end{aligned}$$

since $\theta_1/\theta_3 \ll \theta_2$, $a_i \geq n^{1/2}$ and n is sufficiently large.

Now we apply Lemma 19 to B where M_1 is the identity matching (i.e. every vertex in V_1 is matched to its copy in V_2). Then a cycle of length 2ℓ in $M_1 \cup M_2$ corresponds to a cycle of length ℓ in G. So, since n is sufficiently large, the number of 1-factors of G containing more than $n/(\log n)^{1/5}$ cycles is at most $e^{-n}\mu(B)$. So there exists a 1-factor F of G which satisfies (i) and (ii). □

4.4. **Rotation-Extension lemma.** The following lemma will be a useful tool when transforming 1-factors into Hamilton cycles. Given such a 1-factor F, we will obtain a path P by cutting up and connecting several cycles in F (as described in the proof sketch in Section 2). We will then apply the lemma to obtain a cycle C containing precisely the vertices of P.

Lemma 20. *Let $0 < 1/m \ll \varepsilon \ll \gamma < 1$. Let G be an oriented graph on $n \geq 2m$ vertices. Suppose that U and V are disjoint subsets of $V(G)$ of size m with the following property:*

(13) *If $S \subseteq U$, $T \subseteq V$ are such that $|S|, |T| \geq \varepsilon m$ then $e_G(S,T) \geq \gamma|S||T|/2$.*

Suppose that $P = u_1 \dots u_k$ is a directed path in G where $u_1 \in V$ and $u_k \in U$. Let X denote the set of inneighbours u_i of u_1 which lie on P so that $u_i \in U$ and $u_{i+1} \in V$. Similarly let Y denote the set of outneighbours u_i of u_k which lie on P so that $u_i \in V$ and $u_{i-1} \in U$. Suppose that $|X|, |Y| \geq \gamma m$. Then there exists a cycle C in G containing precisely the vertices of P such that $|E(C) \backslash E(P)| \leq 5$. Furthermore, $E(P) \backslash E(C)$ consists of edges from X to X^+ and edges from Y^- to Y. (Here X^+ is the set of successors of vertices in X on P and Y^- is the set of predecessors of vertices in Y on P.)

Proof. Clearly we may assume that $u_k u_1 \notin E(G)$. Let X_1 denote the set of the first $\gamma m/2$ vertices in X along P and X_2 the set of the last $\gamma m/2$ vertices in X along P. We define Y_1 and Y_2 analogously. So $X_1, X_2 \subseteq U$ and $Y_1, Y_2 \subseteq V$. We have two cases to consider.

Case 1. All the vertices in X_1 precede those in Y_2 along P.

Partition $X_1 = X_{11} \cup X_{12}$ where X_{11} denotes the set of the first $\gamma m/4$ vertices in X_1 along P. We partition Y_2 into Y_{21} and Y_{22} analogously. Let X_{12}^+ denote the set of successors on P of the vertices in X_{12} and Y_{21}^- the set of predecessors of the vertices in Y_{21}. So $X_{12}^+ \subseteq V$ and $Y_{21}^- \subseteq U$. Further define

- $X'_{11} := \{u_i \mid u_{i-1} \in X_{11}$ and $\exists$ edge from u_{i-1} to $X_{12}^+\}$ and
- $Y'_{22} := \{u_i \mid u_{i+1} \in Y_{22}$ and $\exists$ edge from Y_{21}^- to $u_{i+1}\}$.

So $X'_{11} \subseteq V$ and $Y'_{22} \subseteq U$.

From (13) it follows that $|X'_{11}| \geq \frac{(\gamma/2)(\gamma m/4)|X_{12}^+|}{|X_{12}^+|} \geq \varepsilon m$ and similarly $|Y'_{22}| \geq \varepsilon m$. Since $X'_{11} \subseteq V$ and $Y'_{22} \subseteq U$, by (13) G contains an edge $u_{i'}u_i$ from Y'_{22} to X'_{11}. Since $u_i \in X'_{11}$, by definition of X'_{11} it follows that G contains an edge $u_{i-1}u_j$ for some $u_j \in X_{12}^+$. Likewise, since $u_{i'} \in Y'_{22}$, there is an edge $u_{j'}u_{i'+1}$ for some $u_{j'} \in Y_{21}^-$. Furthermore, $u_{j-1}u_1$ and $u_k u_{j'+1}$ are edges of G by definition of X_{12}^+ and Y_{21}^-. It is easy to check that the cycle

$$C = u_1 \dots u_{i-1}u_j u_{j+1} \dots u_{j'}u_{i'+1}u_{i'+2} \dots u_k u_{j'+1}u_{j'+2} \dots u_{i'}u_i u_{i+1} \dots u_{j-1}u_1$$

has the required properties (see Figure 1). For example, $E(P)\backslash E(C)$ consists of the edges $u_{i-1}u_i$, $u_{j-1}u_j$, $u_{j'}u_{j'+1}$ and $u_{i'}u_{i'+1}$. The former two edges go from X to X^+ and the latter two from Y^- to Y.

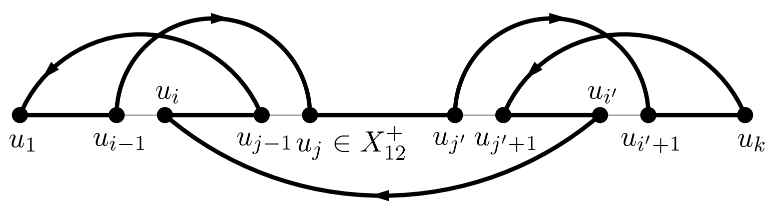

FIGURE 1. The cycle C from Case 1

Case 2. All the vertices in Y_1 precede those in X_2 along P.

Let Y_1^- be the predecessors of the vertices in Y_1 and X_2^+ the successors of the vertices in X_2 on P. So $|Y_1^-| = |X_2^+| = \gamma m/2$ and $Y_1^- \subseteq U$ and $X_2^+ \subseteq V$. Thus by (13) there exists an edge $u_i u_j \in E(G)$ from Y_1^- to X_2^+. Again, it is easy to check that the cycle

$$C = u_1 \dots u_i u_j u_{j+1} \dots u_k u_{i+1} u_{i+2} \dots u_{j-1} u_1$$

has the desired properties. □

4.5. **Shifted walks.** Suppose R is a digraph and F is a collection of vertex-disjoint cycles with $V(F) \subseteq V(R)$. A *closed shifted walk W in R with respect to F* is a walk in $R \cup F$ of the form

$$W = c_1^+ C_1 c_1 c_2^+ C_2 c_2 \dots c_{s-1}^+ C_{s-1} c_{s-1} c_s^+ C_s c_s c_1^+,$$

where

- $\{C_1, \dots, C_s\}$ is the set of all cycles in F;
- c_i lies on C_i and c_i^+ is the successor of c_i on C_i for each $1 \le i \le s$;
- $c_i c_{i+1}^+$ is an edge of R (here $c_{s+1}^+ := c_1^+$).

Note that the cycles $C_1, \dots, C_s$ are not necessarily distinct. If a cycle C_i in F appears exactly t times in W we say that C_i is *traversed t times.* Note that a closed shifted walk W has the property that for every cycle C of F, every vertex of C is visited the same number of times by W. The next lemma will be used in Section 5.7 to combine cycles of G which correspond to different cycles of F into a single (Hamilton) cycle. Shifted walks were introduced in [19], where they were used for a similar purpose.

Lemma 21. *Let $0 < 1/n \ll 1/M' \ll \varepsilon \ll \eta \ll d \ll c \ll d' \ll 1$. Suppose that G is an oriented graph of order n with $\delta^0(G) \ge (1/2 - \eta)n$. Let R denote the reduced digraph of G with parameters ε, d and M' obtained by applying Lemma 9. Let $L := |R|$. Let R' denote the spanning subgraph of R obtained by deleting all edges which correspond to pairs of density at most d' in the pure digraph G'. Let F be a collection of vertex-disjoint cycles with $V(F) \subseteq V(R')$ and $|V(F)| \ge (1-c)L$. Then R' contains a closed shifted walk with respect to F so that each cycle C in F is traversed at most $3L$ times.*

Proof. Let $C_1, \dots, C_t$ denote the cycles of F. We construct our closed shifted walk W as follows: for each cycle C_i, choose an arbitrary vertex a_i lying on C_i and let a_i^+ denote its successor on C_i. Let $U_i := N^+_{R'}(a_i) \cap V(F)$ and let U_i^- be the set of predecessors of U_i on F. Similarly, let $V_i := N^-_{R'}(a_i^+) \cap V(F)$ and let V_i^+ be the set of successors of V_i on F. Since $\delta^0(R') \ge (1/2 - 2d')L$ by Lemma 14(ii), we have $|U_i^-| = |U_i| \ge (1/2 - 3d')L$ and $|V_i^+| = |V_i| \ge (1/2 - 3d')L$. So by Lemma 14(ii) there is an edge $u_i^- v_{i+1}^+$ from U_i^- to V_{i+1}^+ in R'. Then we obtain a walk W_i from a_i^+ to a_{i+1} by first traversing C_i to reach a_i, then use the edge from a_i to the successor u_i of u_i^-, then traverse the cycle in F containing u_i as far as u_i^-, then use the edge $u_i^- v_{i+1}^+$, then traverse the cycle in F containing v_{i+1}^+ as far as v_{i+1}, and finally use the edge $v_{i+1}a_{i+1}$. (Here $a_{t+1} := a_1$.) W is obtained by concatenating the W_i. □

5. Proof of Theorem 3

5.1. **Applying the Diregularity lemma.** Without loss of generality we may assume that $0 < \eta_1 \ll 1$. Define further constants satisfying

(14)
$$0 < 1/M' \ll \varepsilon \ll \beta \ll \eta_2 \ll d \ll c \ll c' \ll \gamma_1 \ll \gamma_2 \ll \gamma_3 \ll \gamma_4 \ll \gamma_5 \ll d' \ll \gamma \ll \eta_1.$$

Let G be an oriented graph of order $n \gg M'$ such that $\delta^0(G) \ge (1/2 - \eta_2)n$. Apply the Diregularity lemma (Lemma 9) to G with parameters ε, d and M' to obtain clusters $V_1, \dots, V_L$ of size m, an exceptional set V_0, a pure digraph G' and a reduced digraph R (so $L = |R|$). Let R' be the spanning subdigraph of R whose edges correspond to pairs of density at least d'. So V_iV_j is an edge of R' if $(V_i, V_j)_{G'}$ has density at least d'.

Let R_m denote the reduced multidigraph of G with parameters ε, β, d and M'. For each edge V_iV_j of R let $d_{i,j}$ denote the density of the ε-regular pair $(V_i, V_j)_{G'}$. Recall that each edge $(V_iV_j)_k \in E(R_m)$ is associated with the kth spanning subgraph $S_{i,j,k}$

of $(V_i, V_j)_{G'}$ obtained by applying Lemma 10 with parameters $\varepsilon, d_{i,j}$ and $K := d_{i,j}/\beta$. Each $S_{i,j,k}$ is ε-regular with density $\beta \pm \varepsilon$. Lemma 11 implies that

$$\delta^0(R_m) \geq (1/2 - 4d)\frac{L}{\beta} \quad \text{and} \quad \Delta^0(R_m) \leq (1/2 + 2\eta_2)\frac{L}{\beta}. \tag{15}$$

(The second inequality holds since $\Delta^0(G) \leq n - \delta^0(G) \leq (1/2 + \eta_2)n$.) Apply Lemma 15 to R_m in order to obtain

$$r := (1 - \gamma)L/2\beta \tag{16}$$

edge-disjoint collections $\mathcal{F}_1, \dots, \mathcal{F}_r$ of vertex-disjoint cycles in R_m such that each $\mathcal{F}_i$ contains all but at most cL of the clusters in R_m. Let $V_{0,i}$ denote the set of all those vertices in G which do not lie in clusters covered by $\mathcal{F}_i$. So $V_0 \subseteq V_{0,i}$ for all $1 \leq i \leq r$ and $|V_{0,i}| \leq |V_0| + cLm \leq (\varepsilon + c)n$. We now apply Lemma 12 to each cycle in $\mathcal{F}_i$ to obtain subclusters of size $m' := (1 - 4\varepsilon)m$ such that the edges of $\mathcal{F}_i$ now correspond to $(10\varepsilon, \beta)$-super-regular pairs. By removing one extra vertex from each cluster if necessary we may assume that m' is even. All vertices not belonging to the chosen subclusters of $\mathcal{F}_i$ are added to $V_{0,i}$. So now

$$|V_{0,i}| \leq 2cn. \tag{17}$$

We refer to the chosen subclusters as the clusters of $\mathcal{F}_i$ and still denote these clusters by $V_1, \dots, V_L$. (This is a slight abuse of notation since the clusters of $\mathcal{F}_i$ might be different from those of $\mathcal{F}_{i'}$.) Thus an edge $(V_{j_1}V_{j_2})_k$ in $\mathcal{F}_i$ corresponds to the $(10\varepsilon, \beta)$-super-regular pair $S'_{j_1,j_2,k} := (V_{j_1}, V_{j_2})_{S_{j_1,j_2,k}}$.

Let C_i denote the oriented subgraph of G whose vertices are all those vertices belonging to clusters in $\mathcal{F}_i$ such that for each $(V_{j_1}V_{j_2})_k \in E(\mathcal{F}_i)$ the edges between V_{j_1} and V_{j_2} are precisely all the edges in $S'_{j_1,j_2,k}$. Clearly $C_1, \dots, C_r$ are edge-disjoint.

We now define 'random' edge-disjoint oriented subgraphs H_1^+, H_1^-, H_2, $H_{3,i}$, H_4 and $H_{5,i}$ of G (for each $i = 1, \dots, r$). H_1^+ and H_1^- will be used in Section 5.2 to incorporate the exceptional vertices in $V_{0,i}$ into C_i. H_2 will be used to choose the skeleton walks in Section 5.4. The $H_{3,i}$ will be used in Section 5.6 to merge certain cycles. H_4 and the $H_{5,i}$ will be used in Section 5.7 to find our almost decomposition into Hamilton cycles. We will choose these subgraphs to satisfy the following properties:

Properties of H_1^+ and H_1^-.

- H_1^+ is a spanning oriented subgraph of G.
- For all $x \in V(H_1^+)$, $\gamma_1 n \leq d^{\pm}_{H_1^+}(x) \leq 2\gamma_1 n$.
- For all $x \in V(H_1^+)$ and each $1 \leq i \leq r$, $|N^{\pm}_{H_1^+}(x) \cap V_{0,i}| \leq 4\gamma_1 |V_{0,i}|$.
- H_1^- satisfies analogous properties.

Properties of H_2.

- The vertex set of H_2 consists of precisely all those vertices of G which lie in a cluster of R (i.e. $V(H_2) = V(G) \setminus V_0$).
- For each edge $(V_{j_1}V_{j_2})_k$ of R_m, H_2 contains a spanning oriented subgraph of $S_{j_1,j_2,k}$ which forms an ε-regular pair of density at least $\gamma_2\beta$.
- All edges of H_2 belong to one of these ε-regular pairs.

- For all $x \in V(H_2)$, $d^{\pm}_{H_2}(x) \leq 2\gamma_2 n$.

Properties of each $H_{3,i}$.

- The vertex set of $H_{3,i}$ consists of precisely all those vertices of G which lie in a cluster of $\mathcal{F}_i$ (i.e. $V(H_{3,i}) = V(G) \setminus V_{0,i}$).
- For each edge $(V_{j_1}V_{j_2})_k$ of $\mathcal{F}_i$, $H_{3,i}$ contains a spanning oriented subgraph of $S'_{j_1,j_2,k}$ which forms a $(\sqrt{\varepsilon}/2, 2\gamma_3\beta)$-super-regular pair.
- All edges in $H_{3,i}$ belong to one of these pairs.
- Let H_3 denote the union of all the oriented graphs $H_{3,i}$. The last two properties together with (16) imply that $d^{\pm}_{H_3}(x) \leq 3\gamma_3 n$ for all $x \in V(H_3)$.

Properties of H_4.

- The vertex set of H_4 consists of precisely all those vertices of G which lie in a cluster of R' (i.e. $V(H_4) = V(G) \setminus V_0$).
- For each edge $V_{j_1}V_{j_2}$ of R', $(V_{j_1}, V_{j_2})_{H_4}$ is ε-regular of density at least $\gamma_4 d'$.
- All edges in H_4 belong to one of these ε-regular pairs.
- For all $x \in V(H_4)$, $d^{\pm}_{H_4}(x) \leq 2\gamma_4 n$.

Properties of each $H_{5,i}$.

- The vertex set of $H_{5,i}$ consists of precisely all those vertices of G which lie in a cluster of $\mathcal{F}_i$.
- For each edge $(V_{j_1}V_{j_2})_k$ of $\mathcal{F}_i$, $H_{5,i}$ contains a spanning oriented subgraph of $S'_{j_1,j_2,k}$ which forms a $(\sqrt{\varepsilon}/2, 2\gamma_5\beta)$-super-regular pair.
- All edges in $H_{5,i}$ belong to one of these pairs.
- Let H_5 denote the union of all the oriented graphs $H_{5,i}$. The last two properties together with (16) imply that $d^{\pm}_{H_5}(x) \leq 3\gamma_5 n$ for all $x \in V(H_5)$.

Properties of each $S'_{i,j,k}$.

- For each edge $(V_{j_1}V_{j_2})_k$ of $\mathcal{F}_i$ the oriented subgraph obtained from $S'_{j_1,j_2,k}$ by removing all the edges in $H_1^+, H_1^-, H_2, \dots, H_5$ is $(\varepsilon^{1/3}, \beta_1)$-super-regular for some β_1 with

$$(1-\gamma)\beta \leq \beta_1 \leq \beta. \tag{18}$$

The existence of H_1^+, H_1^-, H_2, $H_{3,i}$, H_4 and $H_{5,i}$ can be shown by considering suitable random subgraphs of G and applying the Chernoff bound in Proposition 8. For example, to show that H_1^+ exists, consider a random subgraph of G which is obtained by including each edge of G with probability $3\gamma_1$. Similarly, to define H_2 choose every edge in $S_{j_1,j_2,k}$ with probability $3\gamma_2/2$ (for all $S_{j_1,j_2,k}$) and argue as in the proof of Lemma 10. Note that since H_4 only consists of edges between pairs of clusters V_{j_1}, V_{j_2} which form an edge in R', the oriented subgraphs obtained from the $S'_{j_1,j_2,k}$ by deleting all the edges in $H_1^+, H_1^-, H_2, \dots, H_5$ may have densities which differ too much from each other. Indeed, if $V_{j_1}V_{j_2} \notin E(R')$, then the corresponding density will be larger. However, for such pairs we can delete approximately a further γ_4-proportion of the edges to ensure this property holds. Again, the deletion is done by considering a random subgraph obtained by deleting edges with probability γ_4.

We now remove the edges in $H_1^+, H_1^-, H_2, \dots, H_5$ from each C_i. We still refer to the subgraphs of C_i and $S'_{j_1,j_2,k}$ thus obtained as C_i and $S'_{j_1,j_2,k}$.

5.2. **Incorporating $V_{0,i}$ into C_i.** Our ultimate aim is to use each of the C_i as a 'framework' to piece together roughly $\beta_1 m'$ Hamilton cycles in G. In this section we will incorporate the vertices in $V_{0,i}$, together with some edges incident to these vertices, into C_i. For each $i = 1, \dots, r$, let G_i denote the oriented spanning subgraph of G obtained from C_i by adding the vertices of $V_{0,i}$. So initially G_i contains no edges with a start- or endpoint in $V_{0,i}$. We now wish to add edges to G_i so that

(i) $d^{\pm}_{G_i}(x) \geq (1-\sqrt{c})\beta_1 m'$ where x has neighbours only in C_i, for all $x \in V_{0,i}$;
(ii) $|N^{\pm}_{G_i}(y) \cap V_{0,i}| \leq \sqrt{c}\beta_1 m'$ for all $y \in V(C_i)$;
(iii) $G_1, \dots, G_r$ are edge-disjoint.

For each $x \in V(G)$ we define $\mathcal{L}_x := \{i \mid x \in V_{0,i}\}$ and let $L_x := |\mathcal{L}_x|$. To satisfy (i), we need to find roughly $L_x \beta_1 m'$ edges sent out by x (as well as $L_x\beta_1 m'$ edges received by x) such that none of these edges already lies in any of the C_i. It is not hard to check that such edges exist (c.f. (21) below). However, if L_x is small then there is not much choice to which G_i with $i \in \mathcal{L}_x$ we add each of these edges and so it might not be possible to guarantee (ii). For this reason we reserved H_1^+ and H_1^- in advance and for all those x for which L_x is small we will use the edges at x lying in these two graphs. More precisely, let

$$B' := \left\{ x \in V(G) \mid L_x \geq \frac{\gamma_1 n}{2\beta_1 m'} \right\}.$$

As indicated above, we now consider the vertices in B' and $V(G)\backslash B'$ separately.

First consider any $x \in V(G) \setminus B'$. Let $p := 2\beta_1 m'/\gamma_1 n$ and consider each edge e sent out by x in H_1^+. With probability $L_x p \leq 1$ we will assign e to exactly one of the G_i with $i \in \mathcal{L}_x$. More precisely, for each $i \in \mathcal{L}_x$ we assign e to G_i with probability p. So the probability e is not assigned to any of the G_i is $1 - L_x p \geq 0$. We randomly distribute the edges of H_1^- received by x in an analogous way amongst all the G_i with $i \in \mathcal{L}_x$.

We proceed similarly for all the vertices in $V(G) \setminus B'$, with the random choices being independent for different such vertices. Since H_1^+ and H_1^- are edge-disjoint from each other and from all the C_i, the oriented graphs obtained from $G_1, \dots, G_r$ in this way will still be edge-disjoint. Moreover, $\mathbb{E}(d^{\pm}_{G_i}(x)) \geq \gamma_1 np$ and $\mathbb{E}(d^{\pm}_{G_i[V_{0,i}]}(x)) \leq |V_{0,i}|p \leq 2cnp$ for every $x \in V(G) \setminus B'$ and each $i \in \mathcal{L}_x$. Thus

$$\mathbb{E}(|N^{\pm}_{G_i}(x) \cap V(C_i)|) \geq (\gamma_1 - 2c)np \geq \beta_1 m'. \tag{19}$$

Let $B_i := V_{0,i} \cap B'$ and $\bar{B}_i := V_{0,i} \backslash B'$. Since $|N^{\pm}_{H_1^+ \cup H_1^-}(y) \cap V_{0,i}| \leq 8\gamma_1 |V_{0,i}|$ for every $y \in V(C_i)$ (by definition of H_1^+ and H_1^-) we have that

$$\mathbb{E}(|N^{\pm}_{G_i}(y) \cap \bar{B}_i|) \leq 8\gamma_1 |V_{0,i}|p \overset{(17)}{\leq} 32c\beta_1 m'. \tag{20}$$

Applying the Chernoff bound in Proposition 8 (for the binomial distribution) for each i and summing up the error probabilities for all i we see that with nonzero probability the following properties hold:

- (19) implies that $|N^{\pm}_{G_i}(x) \cap V(C_i)| \geq (1-\sqrt{c})\beta_1 m'$ for every $x \in \bar{B}_i$.
- (20) implies that $|N^{\pm}_{G_i}(y) \cap \bar{B}_i| \leq \sqrt{c}\beta_1 m'/2$ for every $y \in V(C_i)$.

For each i we delete all the edges with both endpoints in $V_{0,i}$ from G_i.

Having dealt with the vertices in $V(G)\backslash B'$, let us now consider any $x \in B'$. We call each edge of G with startpoint x *free* if it does not lie in any of C_i, $H_1^+, H_1^-, H_2, \dots, H_5$ (for all $i = 1, \dots, r$) and if the endpoint is not in B'. Note that

$$|B'|\frac{\gamma_1 n}{2\beta_1 m'} \leq \sum_{i=1}^{r} |V_{0,i}| \overset{(17)}{\leq} 2crn \overset{(16)}{\leq} cn\frac{L}{\beta},$$

and so $|B'| \leq \frac{2cn}{\gamma_1}$. So the number of free edges sent out by x is at least

$$\begin{aligned}
&(1/2-\eta_2)n - (\beta_1+\varepsilon^{1/3})m'(r-L_x) - 4\gamma_1 n - 2\gamma_2 n - 3\gamma_3 n - 2\gamma_4 n - 3\gamma_5 n - |B'| \\
&\overset{(16)}{\geq} (1/2-\eta_2)n - (\beta+\varepsilon^{1/3})m'(1-\gamma)\frac{L}{2\beta} + L_x\beta_1 m' - 4\gamma_5 n - \frac{2cn}{\gamma_1} \\
&\overset{(14)}{\geq} (1/2-\eta_2)n - \left(\frac{\varepsilon^{1/3}n}{2\beta} + \frac{n}{2}\right) + \frac{\gamma n}{4} + L_x\beta_1 m' - 5\gamma_5 n \overset{(14)}{\geq} L_x\beta_1 m'. \qquad (21)
\end{aligned}$$

We consider $L_x\beta_1 m'$ of these free edges sent out by x and distribute them randomly amongst all the G_i with $i \in \mathcal{L}_x$. More precisely, each such edge is assigned to G_i with probability $1/L_x$ (for each $i \in \mathcal{L}_x$). So for each $i \in \mathcal{L}_x$,

$$\mathbb{E}(d^+_{G_i}(x)) = \beta_1 m' \qquad (22)$$

and

$$\mathbb{E}(d^+_{G_i[V_{0,i}]}(x)) \leq |V_{0,i}|\frac{1}{L_x} \overset{(17)}{\leq} 2cn\left(\frac{2\beta_1 m'}{\gamma_1 n}\right) = \frac{4c\beta_1 m'}{\gamma_1} \ll \sqrt{c}\beta_1 m'/4. \qquad (23)$$

We can introduce an analogous definition of a free edge at x but for edges whose endpoint is x. As above we randomly distribute $L_x\beta_1 m'$ such edges amongst all the G_i with $i \in \mathcal{L}_x$. Thus for each $i \in \mathcal{L}_x$,

$$\mathbb{E}(d^-_{G_i}(x)) = \beta_1 m' \quad \text{and} \quad \mathbb{E}(d^-_{G_i[V_{0,i}]}(x)) \ll \sqrt{c}\beta_1 m'/4. \qquad (24)$$

We proceed similarly for all vertices in B', with the random choices being independent for different vertices $x \in B'$. (Note that every edge of G is free with respect to at most one vertex in B'.) Then using the lower bound on L_x for all $x \in B'$ we have

$$\mathbb{E}(|N^{\pm}_{G_i}(y) \cap B_i|) \leq |V_{0,i}|\frac{2\beta_1 m'}{\gamma_1 n} \overset{(17)}{\leq} \sqrt{c}\beta_1 m'/4 \qquad (25)$$

for each $i = 1, \dots, r$ and all $y \in V(C_i)$. As before, applying the Chernoff type bound in Proposition 8 for each i and summing up the failure probabilities over all i shows that with nonzero probability the following properties hold:

- (22)–(24) imply that $|N^{\pm}_{G_i}(x) \cap V(C_i)| \geq (1-\sqrt{c})\beta_1 m'$ for each $x \in B_i$.
- (25) implies that $|N^{\pm}_{G_i}(y) \cap B_i| \leq \sqrt{c}\beta_1 m'/2$ for each $y \in V(C_i)$.

Together with the properties of G_i established after choosing the edges at the vertices in $V(G)\setminus B'$ it follows that $|N^{\pm}_{G_i}(x)\cap V(C_i)|\geq (1-\sqrt{c})\beta_1 m'$ for every $x\in V_{0,i}$ and $|N^{\pm}_{G_i}(y)\cap V_{0,i}|\leq \sqrt{c}\beta_1 m'$ for every $y\in V(C_i)$. Furthermore, $G_1,\dots,G_r$ are still edge-disjoint since when dealing with the vertices in B' we only added free edges. By discarding any edges assigned to G_i which lie entirely in $V_{0,i}$ we can ensure that (i) holds. So altogether (i)–(iii) are satisfied, as desired.

5.3. **Randomly splitting the G_i.** As mentioned in the previous section we will use each of the G_i to piece together roughly $\beta_1 m'$ Hamilton cycles of G. We will achieve this by firstly adding some more special edges to each G_i (see Section 5.4) and then almost decomposing each G_i into 1-factors. However, in order to use these 1-factors to create Hamilton cycles we will need to ensure that no 1-factor contains a 2-path with start- and endpoint in $V_{0,i}$, and midpoint in C_i. Unfortunately G_i might contain such paths. To avoid them, we will 'randomly split' each G_i.

We start by considering a random partition of each $V\in V(\mathcal{F}_i)$. Using the Chernoff bound in Proposition 8 for the hypergeometric distribution one can show that there exists a partition of V into subclusters V' and V'' so that the following conditions hold:

- $|V'|,|V''|=m'/2$ for each $V\in V(\mathcal{F}_i)$.
- $|N^{\pm}_{G_i}(x)\cap \mathcal{V}'|\geq (1/2-\sqrt{c})\beta_1 m'$ and $|N^{\pm}_{G_i}(x)\cap \mathcal{V}''|\geq (1/2-\sqrt{c})\beta_1 m'$ for each $x\in V_{0,i}$. (Here $\mathcal{V}':=\bigcup_{V\in V(\mathcal{F}_i)}V'$ and $\mathcal{V}'':=\bigcup_{V\in V(\mathcal{F}_i)}V''$.)

Recall that each edge $(V_{j_1}V_{j_2})_k\in E(\mathcal{F}_i)$ corresponds to the $(\varepsilon^{1/3},\beta_1)$-super-regular pair $S'_{j_1,j_2,k}$. Let $\beta_2:=\beta_1/2$. So

$$(1/2-\gamma)\beta \overset{(18)}{\leq} \beta_2 \overset{(18)}{\leq} \beta/2. \tag{26}$$

Apply Lemma 10(ii) to obtain a partition $E'_{j_1,j_2,k},E''_{j_1,j_2,k}$ of the edge set of $S'_{j_1,j_2,k}$ so that the following condition holds:

- The edges of $E'_{j_1,j_2,k}$ and $E''_{j_1,j_2,k}$ both induce an $(\varepsilon^{1/4},\beta_2)$-super-regular pair which spans $S'_{j_1,j_2,k}$.

We now partition G_i into two oriented spanning subgraphs G'_i and G''_i as follows.

- The edge set of G'_i is the union of all $E'_{j_1,j_2,k}$ (over all edges $(V_{j_1}V_{j_2})_k$ of $\mathcal{F}_i$) together with all the edges in G_i from $V_{0,i}$ to $\mathcal{V}'$, and all edges in G_i from $\mathcal{V}''$ to $V_{0,i}$.
- The edge set of G''_i is the union of all $E''_{j_1,j_2,k}$ (over all edges $(V_{j_1}V_{j_2})_k$ of $\mathcal{F}_i$) together with all the edges in G_i from $V_{0,i}$ to $\mathcal{V}''$, and all edges in G_i from $\mathcal{V}'$ to $V_{0,i}$.

Note that neither G'_i nor G''_i contains the type of 2-paths we wish to avoid. For each $i=1,\dots,r$ we use Lemma 10(ii) to partition the edge set of each $H_{3,i}$ to obtain edge-disjoint oriented spanning subgraphs $H'_{3,i}$ and $H''_{3,i}$ so that the following condition holds:

- For each edge $(V_{j_1}V_{j_2})_k$ in $\mathcal{F}_i$, both $H'_{3,i}$ and $H''_{3,i}$ contain a spanning oriented subgraph of $S'_{j_1,j_2,k}$ which is $(\sqrt{\varepsilon}, \gamma_3\beta)$-super-regular. Moreover, all edges in $H'_{3,i}$ and $H''_{3,i}$ belong to one of these pairs.

Similarly we partition the edge set of each $H_{5,i}$ to obtain edge-disjoint oriented spanning subgraphs $H'_{5,i}$ and $H''_{5,i}$ so that the following condition holds:

- For each edge $(V_{j_1}V_{j_2})_k$ in $\mathcal{F}_i$, both $H'_{5,i}$ and $H''_{5,i}$ contain a spanning oriented subgraph of $S'_{j_1,j_2,k}$ which is $(\sqrt{\varepsilon}, \gamma_5\beta)$-super-regular. Moreover, all edges in $H'_{5,i}$ and $H''_{5,i}$ belong to one of these pairs.

We pair $H'_{3,i}$ and $H'_{5,i}$ with G'_i and pair $H''_{3,i}$ and $H''_{5,i}$ with G''_i. We now have $2r$ edge-disjoint oriented subgraphs of G, namely $G'_1, G''_1, \dots, G'_r, G''_r$. To simplify notation, we relabel these oriented graphs as $G_1, \dots, G_{r'}$ where

$$r' := 2r \overset{(16)}{=} (1-\gamma)L/\beta. \tag{27}$$

We similarly relabel the oriented graphs $H'_{3,1}, H''_{3,1}, \dots, H'_{3,r}, H''_{3,r}$ as $H_{3,1}, \dots, H_{3,r'}$ and relabel $H'_{5,1}, H''_{5,1}, \dots, H'_{5,r}, H''_{5,r}$ as $H_{5,1}, \dots, H_{5,r'}$ in such a way that $H_{3,i}$ and $H_{5,i}$ are the oriented graphs which we paired with G_i. For each i we still use the notation $\mathcal{F}_i$, C_i and $V_{0,i}$ in the usual way. Now (i) from Section 5.2 becomes

(i′) $d^{\pm}_{G_i}(x) \geq (1/2 - \sqrt{c})\beta_1 m'$ where x has neighbours only in C_i, for all $x \in V_{0,i}$,

while (ii) and (iii) remain valid.

5.4. **Adding skeleton walks to the G_i.** Note that all vertices (including the vertices of $V_{0,i}$) in each G_i now have in- and outdegree close to $\beta_2 m'$. In Section 5.5 our aim is to find a τ-regular oriented subgraph of G_i, where

$$\tau := (1-\gamma)\beta_2 m'. \tag{28}$$

However, this may not be possible: suppose for instance that $V_{0,i}$ consists of a single vertex x, $\mathcal{F}_i$ consists of 2 cycles C and C' and that all outneighbours of x lie on C and all inneighbours lie on C'. Then G_i does not even contain a 1-factor. A similar problem arises if for example $V_{0,i}$ consists of a single vertex x, $\mathcal{F}_i$ consists of a single cycle $C = V_1 \dots V_t$, all outneighbours of x lie in the cluster V_2 and all inneighbours in the cluster V_8. Note that in both situations, the edges between $V_{0,i}$ and C_i are not 'well-distributed' or 'balanced'. To overcome this problem, we add further edges to C_i which will 'balance out' the edges between C_i and $V_{0,i}$ which we added previously. These edges will be part of the skeleton walks which we define below. To motivate the definition of the skeleton walks it may be helpful to consider the second example above: Suppose that we add an edge e from V_1 to V_9. Then G_i now has a 1-factor. In general, we cannot find such an edge, but it will turn out that we can find a collection of 5 edges fulfilling the same purpose.

A *skeleton walk* S in G with respect to G_i is a collection of distinct edges x_1x_2, $x_2^-x_3$, $x_3^-x_4$, $x_4^-x_5$ and $x_5^-x_1$ of G with the following properties:

- $x_1 \in V_{0,i}$ and all vertices in $V(S)\setminus\{x_1\}$ lie in C_i.

- Given some $2 \leq j \leq 5$, let $V \in V(\mathcal{F}_i)$ denote the cluster in $\mathcal{F}_i$ containing x_j and let C denote the cycle in $\mathcal{F}_i$ containing V. Then $x_j^- \in V^-$, where V^- is the predecessor of V on C.

Note that whenever $\mathcal{S}$ is a union of edge-disjoint skeleton walks and V is a cluster in $\mathcal{F}_i$, the number of edges in $\mathcal{S}$ whose endpoint is in V is the same as the number of edges in $\mathcal{S}$ whose startpoint is in V^-. As indicated above, this 'balanced' property will be crucial when finding a τ-regular oriented subgraph of G_i in Section 5.5.

The 2nd, 3rd and 4th edge of each skeleton walk S with respect to G_i will lie in the 'random' graph H_2 chosen in Section 5.1. More precisely, each of these three edges will lie in a 'slice' $H_{2,i}$ of H_2 assigned to G_i. We will now partition H_2 into these 'slices' $H_{2,1}, \dots, H_{2,r'}$. To do this, recall that any edge $(V_{j_1}V_{j_2})_k$ in R_m corresponds to an ε-regular pair of density at least $\gamma_2\beta$ in H_2. Here V_{j_1} and V_{j_2} are viewed as clusters in R_m, so $|V_{j_1}| = |V_{j_2}| = m$. Apply Lemma 10(i) to each such pair of clusters to find edge-disjoint oriented subgraphs $H_{2,1}, \dots, H_{2,r'}$ of H_2 so that for each $H_{2,i}$ all the edges $(V_{j_1}V_{j_2})_k$ in R_m correspond to $[\varepsilon, 5\beta\varepsilon/L]$-regular pairs with density at least $(\gamma_2\beta - 2\varepsilon)\beta/L \geq \gamma_2\beta^2/2L$ in $H_{2,i}$.

Recall that by (i$'$) in Section 5.3 each vertex $x \in V_{0,i}$ has at least $(1/2-\sqrt{c})\beta_1 m' \geq \tau$ outneighbours in C_i and at least $(1/2 - \sqrt{c})\beta_1 m'$ inneighbours in C_i. We pair τ of these outneighbours x^+ with distinct inneighbours x^-. For each of these τ pairs x^+, x^- we wish to find a skeleton walk with respect to G_i whose 1st edge is xx^+ and whose 5th edge is x^-x. We denote the union of these τ pairs xx^+, x^-x of edges over all $x \in V_{0,i}$ by $\mathcal{T}_i$.

In Section 5.3 we partitioned each cluster $V \in V(\mathcal{F}_i)$ into subclusters V' and V''. We next show how to choose the skeleton walks for all those G_i for which each edge in G_i with startpoint in $V_{0,i}$ has its endpoint in $\mathcal{V}'$ (and so each edge in G_i with endpoint in $V_{0,i}$ has startpoint in $\mathcal{V}''$). The other case is similar, one only has to interchange $\mathcal{V}'$ and $\mathcal{V}''$.

Claim 22. *We can find a set $\mathcal{S}_i$ of $\tau|V_{0,i}|$ skeleton walks with respect to G_i, one for each pair of edges in $\mathcal{T}_i$, such that $\mathcal{S}_i$ has the following properties:*

- (i) *For each skeleton walk in $\mathcal{S}_i$, its 2nd, 3rd and 4th edge all lie in $H_{2,i}$ and all these edges have their startpoint in $\mathcal{V}''$ and endpoint in $\mathcal{V}'$.*
- (ii) *Any two of the skeleton walks in $\mathcal{S}_i$ are edge-disjoint.*
- (iii) *Every $y \in V(C_i)$ is incident to at most $c^{1/5}\beta_2 m'$ edges belonging to the skeleton walks in $\mathcal{S}_i$.*

Note that $|\mathcal{S}_i| = |\mathcal{T}_i| = \tau|V_{0,i}| \leq 2c\beta_2 m'n$ by (17) and (28). To find $\mathcal{S}_i$, we will first find so-called shadow skeleton walks (here the internal edges are edges of R_m instead of G). More precisely, a *shadow skeleton walk* S' with respect to G_i is a collection of two edges x_1x_2, $x_5^-x_1$ of G and three edges $(X_2^-X_3)_{k_2}$, $(X_3^-X_4)_{k_3}$, $(X_4^-X_5)_{k_4}$ of R_m with the following properties:

- x_1x_2, $x_5^-x_1$ is a pair in $\mathcal{T}_i$.
- $x_2 \in X_2$, $x_5^- \in X_5^-$ and each X_j is a vertex of a cycle in $\mathcal{F}_i$ and X_j^- is the predecessor of X_j on that cycle.

Note that in the second condition we slightly abused the notation: as X_j is a cluster in R_m, it only corresponds to a cluster in $\mathcal{F}_i$ (which has size m' and is a subcluster of the one in R_m). However, in order to simplify our exposition, we will use the same notation for a cluster in R_m as for the cluster in $\mathcal{F}_i$ corresponding to it.

We refer to the edge $(X_j^- X_{j+1})_{k_j}$ as the jth edge of the shadow skeleton walk S'. Given a collection $\mathcal{S}'$ of shadow skeleton walks (with respect to G_i) we say an edge of R_m is *bad* if it is used at least $B := c^{1/4}\beta^2(m')^2/L$ times in $\mathcal{S}'$, and *very bad* if it is used at least $10B$ times in $\mathcal{S}'$. We say an edge from V to U in R_m is $(V,+)$-*bad* if it is used at least B times as a 2nd edge in the shadow skeleton walks of $\mathcal{S}'$. An edge from W to V in R_m is $(V,-)$-*bad* if it is used at least B times as a 4th edge in the shadow skeleton walks of $\mathcal{S}'$.

To prove Claim 22 we will first prove the following result.

Claim 23. *We can find a collection $\mathcal{S}_i'$ of $\tau|V_{0,i}|$ shadow skeleton walks with respect to G_i, one for each of pair in $\mathcal{T}_i$, such that the following condition holds:*

- *For each $2 \leq j \leq 4$, every edge in R_m is used at most B times as a jth edge of some shadow skeleton walk in $\mathcal{S}_i'$. In particular no edge in R_m is very bad.*

Proof. Suppose that we have already found $\ell < \tau|V_{0,i}|$ of our desired shadow skeleton walks for G_i. Let xx^+, x^-x be a pair in $\mathcal{T}_i$ for which we have yet to define a shadow skeleton walk. We will now find such a shadow skeleton walk S'. Suppose $x^+ \in V^+$ and $x^- \in W^-$, where $V^+, W^- \in V(\mathcal{F}_i)$. Let V denote the predecessor of V^+ in $\mathcal{F}_i$ and W the successor of W^- in $\mathcal{F}_i$. We define $\mathcal{V}^+$ to consist of all those clusters $U \in V(\mathcal{F}_i)$ for which there exists an edge from V to U in R_m which is not $(V,+)$-bad. By definition of G_i (condition (ii) in Section 5.2), each $y \in V(C_i)$ has at most $\sqrt{c}\beta_1 m'$ inneighbours in $V_{0,i}$ in G_i. So the number of $(V,+)$-bad edges is at most

$$\frac{\sqrt{c}\beta_1(m')^2}{B} = \frac{\sqrt{c}\beta_1(m')^2}{c^{1/4}\beta^2(m')^2/L} = \frac{c^{1/4}\beta_1 L}{\beta^2} \overset{(18)}{\leq} \frac{c^{1/4}L}{\beta}.$$

Together with (15) this implies that

$$|\mathcal{V}^+| \geq (1/2 - 4d - c^{1/4})L \geq (1/2 - 2c^{1/4})L.$$

Similarly we define $\mathcal{W}^-$ to consist of all those clusters $U \in V(\mathcal{F}_i)$ for which there exists an edge from U to W in R_m which is not $(W,-)$-bad. Again, $|\mathcal{W}^-| \geq (1/2 - 2c^{1/4})L$. Let $\mathcal{V}$ denote the set of those clusters which are the predecessors in $\mathcal{F}_i$ of a cluster in $\mathcal{V}^+$. Similarly let $\mathcal{W}$ denote the set of those clusters which are the successors in $\mathcal{F}_i$ of a cluster in $\mathcal{W}^-$. So $|\mathcal{V}| = |\mathcal{V}^+|$ and $|\mathcal{W}| = |\mathcal{W}^+|$. By Lemma 14(i) applied with $X = V(R_m)$ there exist at least $L^2/60\beta$ edges in R_m from $\mathcal{V}$ to $\mathcal{W}$. On the other hand, the number of bad edges is at most

$$\frac{3\tau|V_{0,i}|}{B} \overset{(17),(28)}{\leq} \frac{6\beta_2 m' cn}{c^{1/4}\beta^2(m')^2/L} \leq \frac{7c^{3/4}\beta_2 L^2}{\beta^2} \overset{(26)}{\leq} \frac{7c^{3/4}L^2}{\beta}.$$

So we can choose an edge $(XY)_k$ from $\mathcal{V}$ to $\mathcal{W}$ in R_m which is not bad. Let X^+ denote the successor of X in $\mathcal{F}_i$ and Y^- the predecessor of Y in $\mathcal{F}_i$. Thus $X^+ \in \mathcal{V}^+$ and $Y^- \in \mathcal{W}^-$ and so there is an edge $(VX^+)_{k'}$ in R_m which is not $(V,+)$-bad and an edge $(Y^-W)_{k''}$ which is not $(W,-)$-bad. Let S' be the shadow skeleton walk consisting of the edges xx^+, $(VX^+)_{k'}$, $(XY)_k$, $(Y^-W)_{k''}$, and x^-x. Then we can add S' to our collection of ℓ skeleton walks that we have found already. $\square$

We now use Claim 23 to prove Claim 22.

Proof of Claim 22. We apply Claim 23 to obtain a collection $\mathcal{S}'_i$ of shadow skeleton walks. We will replace each edge of R_m in these shadow skeleton walks with a distinct edge of $H_{2,i}$ to obtain our desired collection $\mathcal{S}_i$ of skeleton walks.

Recall that each edge $(VW)_k$ in R_m corresponds to an $[\varepsilon, 5\varepsilon\beta/L]$-regular pair of density at least $\gamma_2\beta^2/2L$ in $H_{2,i}$. Thus in $H_{2,i}$ the edges from V'' to W' induce a $[3\varepsilon, 10\varepsilon\beta/L]$-regular pair of density $d_1 \geq \gamma_2\beta^2/3L$. (Here V', V'' and W', W'' are the partitions of V and W chosen in Section 5.3.) Let $d_0 := 80B/(m'/2)^2$ and note that $d_0 \leq d_1$. So we can now apply Lemma 13 to $(V'', W')_{H_{2,i}}$ to obtain a subgraph $H'_{2,i}[V'', W']$ with maximum degree at most $d_0 m'/2$ and at least $d_0(m'/2)^2/8 = 10B$ edges. We do this for all those edges in R_m which are used in a shadow skeleton walk in $\mathcal{S}'_i$.

Since no edge in R_m is very bad, for each $S' \in \mathcal{S}'_i$ we can replace an edge $(VW)_k$ in S' with a distinct edge e from V'' to W' lying in $H'_{2,i}[V'', W']$. Thus we obtain a collection $\mathcal{S}_i$ of skeleton walks which satisfy properties (i) and (ii) of Claim 22. Note that by the construction of $\mathcal{S}_i$ every vertex $y \in V(C_i)$ is incident to at most $d_0 m'L/(2\beta) \ll c^{1/5}\beta_2 m'/2$ edges which play the role of a 2nd, 3rd or 4th edge in a skeleton walk in $\mathcal{S}_i$. Condition (ii) in Section 5.2 implies that y is incident to at most $2\sqrt{c}\beta_1 m'$ edges which play the role of a 1st or 5th edge in a skeleton walk in $\mathcal{S}_i$. So in total y is incident to at most $c^{1/5}\beta_2 m'/2 + 2\sqrt{c}\beta_1 m' \leq c^{1/5}\beta_2 m'$ edges of the skeleton walks in $\mathcal{S}_i$. Hence (iii) and thus the entire claim is satisfied. $\square$

We now add the edges of the skeleton walks in $\mathcal{S}_i$ to G_i. Moreover, for each $x \in V_{0,i}$ we delete all those edges at x which do not lie in a skeleton walk in $\mathcal{S}_i$.

5.5. **Almost decomposing the G_i into 1-factors.** Our aim in this section is to find a suitable collection of 1-factors in each G_i which together cover almost all the edges of G_i. In order to do this, we first choose a τ-regular spanning oriented subgraph G_i^* of G_i and then apply Lemma 17 to G_i^*.

We will refer to all those edges in G_i which lie in a skeleton walk in $\mathcal{S}_i$ as *red*, and all other edges in G_i as *white*. Given $V \in V(\mathcal{F}_i)$ and $x \in V$, we denote by $N^+_w(x)$ the set of all those vertices which receive a white edge from x in G_i. Similarly we denote by $N^-_w(x)$ the set of all those vertices which send out a white edge to x in G_i. So $N^+_w(x) \subseteq V^+$ and $N^-_w(x) \subseteq V^-$, where V^+ and V^- are the successor and the predecessor of V in $\mathcal{F}_i$. Note that G_i has the following properties:

- (α_1) $d^{\pm}_{G_i}(x) = \tau$ for each $x \in V_{0,i}$. Moreover, x does not have any in- or outneighbours in $V_{0,i}$.
- (α_2) Every path in G_i consisting of two red edges has its midpoint in $V_{0,i}$.
- (α_3) For each $(V_jV_j^+)_k \in E(\mathcal{F}_i)$ the white edges in G_i from V_j to V_j^+ induce a $(\varepsilon^{1/4}, \beta_2)$-super-regular pair $(V_j, V_j^+)_{G_i}$.

(α_4) Every vertex $u \in V(C_i)$ receives at most $c^{1/5}\beta_2 m'$ red edges and sends out at most $c^{1/5}\beta_2 m'$ red edges in G_i.

(α_5) In total, the vertices in G_i lying in a cluster $V_j \in V(\mathcal{F}_i)$ send out the same number of red edges as the vertices in V_j^+ receive.

In order to find our τ-regular spanning oriented subgraph of G_i, consider any edge $(V_j V_j^+)_k \in E(\mathcal{F}_i)$. Given any $u_\ell \in V_j$, let x_ℓ denote the number of red edges sent out by u_ℓ in G_i. Similarly given any $v_\ell \in V_j^+$, let y_ℓ denote the number of red edges received by v_ℓ in G_i. By (α_4) we have that $x_\ell, y_\ell \leq c^{1/5}\beta_2 m'$ and by (α_5) we have that

$$\sum_{u_\ell \in V_j} x_\ell = \sum_{v_\ell \in V_j^+} y_\ell.$$

Thus we can apply Lemma 16 to obtain an oriented spanning subgraph of $(V_j, V_j^+)_{G_i}$ in which each u_ℓ has outdegree $\tau - x_\ell$ and each v_ℓ has indegree $\tau - y_\ell$. We apply Lemma 16 to each $(V_j V_j^+)_k \in E(\mathcal{F}_i)$. The union of all these oriented subgraphs together with the red edges in G_i clearly yield a τ-regular oriented subgraph G_i^* of G_i, as desired.

We will use the following claim to almost decompose G_i^* into 1-factors with certain useful properties.

Claim 24. *Let G^* be a spanning ρ-regular oriented subgraph of G_i where $\rho \geq \gamma\beta_2 m'$. Then G^* contains a 1-factor F^* with the following properties:*

(i) *F^* contains at most $n/(\log n)^{1/5}$ cycles.*

(ii) *For each $V_j \in V(\mathcal{F}_i)$, F^* contains at most $c'm'$ red edges incident to vertices in V_j.*

(iii) *Let F^*_{red} denote the set of vertices which are incident to a red edge in F^*. Then $|F^*_{red} \cap N^{\pm}_{H_{3,i}}(x)| \leq 2c'\gamma_3\beta m'$ for each $x \in V(C_i)$.*

(iv) *$|F^*_{red} \cap N^{\pm}_{w}(x)| \leq 2c'\beta_2 m'$ for each $x \in V(C_i)$.*

Proof. A direct application of Lemma 17 to G^* proves the claim. Indeed, we apply the lemma with $\theta_1 = (c^{1/5}\beta_2 m')/n$, $\theta_2 = c'$, $\theta_3 = \rho/n \geq (\gamma\beta_2 m')/n$ and with the oriented spanning subgraph of G^* whose edge set consists precisely of the red edges in G^* playing the role of H. Furthermore, the clusters in $V(\mathcal{F}_i)$ together with the sets $N^{\pm}_w(x)$ and $N^{\pm}_{H_{3,i}}(x)$ (for each $x \in V(C_i)$) play the role of the A_j. □

Repeatedly applying Claim 24 we obtain edge-disjoint 1-factors $F_{i,1}, \dots, F_{i,\psi}$ of G_i satisfying conditions (i)–(iv) of the claim, where

$$\psi := (1 - 2\gamma)\beta_2 m'. \tag{29}$$

Our aim is now to transform each of the $F_{i,j}$ into a Hamilton cycle using the edges of $H_{3,i}$, H_4 and $H_{5,i}$.

5.6. **Merging the cycles in $F_{i,j}$ into a bounded number of cycles.** Let $D_1, \dots, D_\xi$ denote the cycles in $\mathcal{F}_i$ and define $V_G(D_k)$ to be the set of vertices in G_i which lie in clusters in the cycle D_k. In this subsection, for each i and j we will merge the cycles in $F_{i,j}$ to obtain a 1-factor $F'_{i,j}$ consisting of at most ξ cycles.

Recall from Section 5.5 that we call the edges of G_i which lie on a skeleton walk in $\mathcal{S}_i$ red and the non-red edges of G_i white. We call the edges of the 'random' oriented graph $H_{3,i}$ defined in Section 5.1 *green*. (Recall that $H_{3,i}$ was modified in Section 5.3.) We will use the edges from $H_{3,i}$ to obtain 1-factors $F'_{i,1}, \dots, F'_{i,\psi}$ for each G_i with the following properties:

(β_1) If $i \neq i'$ or $j \neq j'$ then $F'_{i,j}$ and $F'_{i',j'}$ are edge-disjoint.
(β_2) For each $V \in V(\mathcal{F}_i)$ all $x \in V$ which send out a white edge in $F_{i,j}$ lie on the same cycle C in $F'_{i,j}$.
(β_3) $|E(F'_{i,j}) \setminus E(F_{i,j})| \leq 6n/(\log n)^{1/5}$ for all i and j. Moreover, $E(F'_{i,j}) \setminus E(F_{i,j})$ consists of green and white edges only.
(β_4) For every edge in $F_{i,j}$ both endvertices lie on the same cycle in $F'_{i,j}$.
(β_5) All the red edges in $F_{i,j}$ still lie in $F'_{i,j}$.

Before showing the existence of 1-factors satisfying (β_1)–(β_5), we will derive two further properties (β_6) and (β_7) from them which we will use in the next subsection. So suppose that $F'_{i,j}$ is a 1-factor satisfying the above conditions. Consider any cluster $V \in V(\mathcal{F}_i)$. Claim 24(ii) implies that $F_{i,j}$ contains at most $c'm'$ red edges with startpoint in V. So the cycle C in $F'_{i,j}$ which contains all vertices $x \in V$ sending out a white edge in $F_{i,j}$ must contain at least $(1-c')m'$ such vertices x. In particular there are at least $(1-c')m' > c'm'$ vertices $y \in V^+$ which lie on C. So some of these vertices y send out a white edge in $F_{i,j}$. But by (β_2) this means that C contains all those vertices $y \in V^+$ which send out a white edge in $F_{i,j}$. Repeating this argument shows that C contains all vertices in $V(D_k)$ which send out a white edge in $F_{i,j}$ (here D_k is the cycle on $\mathcal{F}_i$ that contains V). Furthermore, by property (β_4), C contains all vertices in $V(D_k)$ which receive a white edge in $F_{i,j}$. By property (α_2) in Section 5.5 no vertex of C_i is both the a startpoint of a red edge in G_i and an endpoint of a red edge in G_i. So this implies that all vertices in $V_G(D_k)$ lie on C. Thus if we obtain 1-factors $F'_{i,1}, \dots, F'_{i,\psi}$ satisfying (β_1)–(β_5) then the following conditions also hold:

(β_6) For each $j = 1, \dots, \psi$ and each $k = 1, \dots, \xi$ all the vertices in $V_G(D_k)$ lie on the same cycle in $F'_{i,j}$.
(β_7) For each $V \in V(\mathcal{F}_i)$ and each $j = 1, \dots, \psi$ at most $c'm'$ vertices in V lie on a red edge in $F'_{i,j}$.

(Condition (β_7) follows from Claim 24(ii) and the 'moreover' part of (β_3).)

For every i, we will define the 1-factors $F'_{i,1}, \dots, F'_{i,\psi}$ sequentially. Initially, we let $F'_{i,j} = F_{i,j}$. So the $F'_{i,j}$ satisfy all conditions except (β_2). Next, we describe how to modify $F'_{i,1}$ so that it also satisfies (β_2).

Recall from Section 5.3 that for each edge $(VV^+)_k$ of $\mathcal{F}_i$ the pair $(V, V^+)_{H_{3,i}}$ is $(\sqrt{\varepsilon}, \gamma_3\beta)$-super-regular and thus $\delta^{\pm}(H_{3,i}) \geq (\gamma_3\beta - \sqrt{\varepsilon})m' \geq \gamma_3\beta m'/2$. Furthermore, whenever $V \in V(\mathcal{F}_i)$ and $x \in V$, the outneighbourhood of x in $H_{3,i}$ lies in V^+ and the inneighbourhood of x in $H_{3,i}$ lies in V^-. Let $H'_{3,i}$ denote the oriented spanning subgraph of $H_{3,i}$ whose edge set consists of those edges xy of $H_{3,i}$ for which x is not a startpoint of a red edge in our current 1-factor $F'_{i,1}$ and y is not an endpoint of a red edge in $F'_{i,1}$. Consider a white edge xy in $F'_{i,1}$. Claim 24(iii) implies that

x sends out at most $2c'\gamma_3\beta m'$ green edges xz in $H_{3,i}$ which do not lie in $H'_{3,i}$. So $d^+_{H'_{3,i}}(x) \geq (1/2 - 2c')\gamma_3\beta m'$. Similarly, $d^-_{H'_{3,i}}(y) \geq (1/2 - 2c')\gamma_3\beta m'$. (However, if uv is a red edge in $F'_{i,1}$ then $d^+_{H'_{3,i}}(u) = d^-_{H'_{3,i}}(v) = 0$.) Thus we have the following properties of $H_{3,i}$ and $H'_{3,i}$:

(γ_1) For each $V \in V(\mathcal{F}_i)$ all the edges in $H_{3,i}$ sent out by vertices in V go to V^+.
(γ_2) If xy is a white edge in $F'_{i,1}$ then $d^+_{H'_{3,i}}(x), d^-_{H'_{3,i}}(y) \geq \gamma_3\beta m'/3$.
(γ_3) Consider any $V \in V(\mathcal{F}_i)$. Let $S \subseteq V$ and $T \subseteq V^+$ be such that $|S|, |T| \geq \sqrt{\varepsilon} m'$. Then $e_{H_{3,i}}(S, T) \geq \gamma_3\beta|S||T|/2$.

If $F'_{i,1}$ does not satisfy (β_2), then it contains cycles $C \neq C^*$ such that there is a cluster $V \in V(\mathcal{F}_i)$ and white edges xy on C and x^*y^* on C^* with $x, x^* \in V$ and $y, y^* \in V^+$.

We have 3 cases to consider. Firstly, we may have a green edge $xz \in E(H'_{3,i})$ such that z lies on a cycle $C' \neq C$ in $F'_{i,1}$. Then $z \in V^+$ and z is the endpoint of a white edge in $F'_{i,1}$ (by (γ_1) and the definition of $H'_{3,i}$). Secondly, there may be a green edge $wy^* \in E(H'_{3,i})$ such that w lies on a cycle $C' \neq C^*$ in $F'_{i,1}$. So here $w \in V$ is the startpoint of a white edge in $F'_{i,1}$. If neither of these cases hold, then $N^+_{H'_{3,i}}(x)$ lies on C and $N^-_{H'_{3,i}}(y^*)$ lies on C^*. Since $d^+_{H'_{3,i}}(x), d^-_{H'_{3,i}}(y^*) \geq \gamma_3\beta m'/3$ by (γ_2), we can use (γ_3) to find a green edge $x'y'$ from $N^-_{H'_{3,i}}(y^*)$ to $N^+_{H'_{3,i}}(x)$. Then $x' \in V$, $y' \in V^+$, x' is the startpoint of a white edge in $F'_{i,1}$ and y' is the endpoint of a white edge in $F'_{i,1}$.

We will only consider the first of these 3 cases. The other cases can be dealt with analogously: In the second case w plays the role of x and y^* plays the role of z. In the third case x' plays the role of x and y' plays the role of z.

So let us assume that the first case holds, i.e. there is a green edge $xz \in E(H'_{3,i})$ such that z lies on a cycle $C' \neq C$ in $F'_{i,1}$ and z lies on a white edge wz on C'. Let P denote the directed path $(C \cup C' \cup \{xz\}) \setminus \{xy, wz\}$ from $y \in V^+$ to $w \in V$. Suppose that the endpoint w of P lies on a green edge $wv \in E(H'_{3,i})$ such that v lies outside P. Then $v \in V^+$ is the endpoint of a white edge uv lying on the cycle C'' in $F'_{i,1}$ which contains v. We extend P by replacing P and C'' with $(P \cup C'' \cup \{wv\}) \setminus \{uv\}$. We make similar extensions if the startpoint y of P has an inneighbour in $H'_{3,i}$ outside P. We repeat this 'extension' procedure as long as we can. Let P denote the path obtained in this way, say P joins $a \in V^+$ to $b \in V$. Note that a must be the endpoint of a white edge in $F'_{i,1}$ and b the startpoint of a white edge in $F'_{i,1}$.

We will now apply a 'rotation' procedure to close P into a cycle. By (γ_2) a has at least $\gamma_3\beta m'/3$ inneighbours in $H'_{3,i}$ and b has at least $\gamma_3\beta m'/3$ outneighbours in $H'_{3,i}$ and all these in- and outneighbours lie on P since we could not extend P any further. Let $X := N^-_{H'_{3,i}}(a)$ and $Y := N^+_{H'_{3,i}}(b)$. So $|X|, |Y| \geq \gamma_3\beta m'/3$ and $X \subseteq V$ and $Y \subseteq V^+$ by (γ_1). Moreover, whenever $c \in X$ and c^+ is the successor of c on P, then either cc^+ was a white edge in $F'_{i,1}$ or $cc^+ \in E(H'_{3,i})$. Thus in both cases $c^+ \in V^+$. So the set X^+ of successors in P of all the vertices in X lies in V^+ and no vertex in X sends out a red edge in P. Similarly one can show that the set Y^- of predecessors in P of all the vertices in Y lies in V and no vertex in Y receives a red edge in P. Together with (γ_3) this shows that we can apply Lemma 20 with $P \cup H_{3,i}$ playing the role of G and V^+ playing the role of V and V playing the role of U to obtain a cycle $\hat{C}$ containing precisely the vertices of P such that $|E(\hat{C})\backslash E(P)| \leq 5$, $E(\hat{C})\backslash E(P) \subseteq E(H_{3,i})$ and such that $E(P)\backslash E(\hat{C})$ consists of edges from X to X^+ and edges from Y^- to Y. Thus $E(P)\backslash E(\hat{C})$ contains no red edges. Replacing P with $\hat{C}$ gives us a 1-factor (which we still call $F'_{i,j}$) with fewer cycles. Also note that if the number of cycles is reduced by ℓ, then we use at most $\ell + 5 \leq 6\ell$ edges in $H_{3,i}$ to achieve this. So $F'_{i,j}$ still satisfies all requirements with the possible exception of (β_2). If it still does not satisfy (β_2), we will repeatedly apply this 'rotation-extension' procedure until the current 1-factor $F'_{i,1}$ also satisfies (β_2). However, we need to be careful since we do not want to use edges of $H_{3,i}$ several times in this process. Simply deleting the edges we use may not work as (γ_2) might fail later on (when we will repeat the above process for $F'_{i,j}$ with $j > 1$).

So each time we modify $F'_{i,1}$, we also modify $H_{3,i}$ as follows. All the edges from $H_{3,i}$ which are used in $F'_{i,1}$ are removed from $H_{3,i}$. All the edges which are removed from $F'_{i,1}$ in the rotation-extension procedure are added to $H_{3,i}$. (Note that by (β_5) we never add red edges to $H_{3,i}$.) When we refer to $H_{3,i}$, we always mean the 'current' version of $H_{3,i}$, not the original one. Furthermore, at every step we still refer to an edge of $H_{3,i}$ as green, even if initially the edge did not lie in $H_{3,i}$. Similarly at every step we refer to the non-red edges of our current 1-factor as white, even if initially they belonged to $H_{3,i}$.

Note that if we added a green edge xz into $F'_{i,1}$, then x lost an outneighbour in $H_{3,i}$, namely z. However, (β_5) implies that we also moved some (white) edge xy of $F'_{i,1}$ to $H_{3,i}$, where y lies in the same cluster $V^+ \in V(\mathcal{F}_i)$ as z (here $x \in V$). So we still have that $\delta^+(H_{3,i}) \geq \gamma_3\beta m'/3$. Similarly, at any stage $\delta^-(H_{3,i}) \geq \gamma_3\beta m'/3$. When $H_{3,i}$ is modified, then $H'_{3,i}$ is modified accordingly. This will occur if we add some white edges to $H_{3,i}$ whose start or endpoint lies on a red edge in $F'_{i,1}$. However, Claim 24(iv) implies that at any stage we still have

$$d^+_{H'_{3,i}}(x), d^-_{H'_{3,i}}(y) \geq (1/2 - 2c')\gamma_3\beta m' - 2c'\beta_2 m' \geq \gamma_3\beta m'/3.$$

Also note that by (β_3), the modified version of $H_{3,i}$ still satisfies

$$e_{H_{3,i}}(S,T) \geq (\gamma_3\beta - \sqrt{\varepsilon})|S||T| - 6n/(\log n)^{1/5} \geq \gamma_3\beta|S||T|/2. \tag{30}$$

So $H_{3,i}$ and $H'_{3,i}$ will satisfy (γ_1)–(γ_3) throughout and thus the above argument still works. So after at most $n/(\log n)^{1/5}$ steps $F'_{i,1}$ will also satisfy (β_2).

Suppose that for some $1 < j \leq \psi$ we have found 1-factors $F'_{i,1}, \dots, F'_{i,j-1}$ satisfying (β_1)–(β_5). We can now carry out the rotation-extension procedure for $F'_{i,j}$ in the same way as for $F'_{i,1}$ until $F'_{i,j}$ also satisfies (β_2). In the construction of $F'_{i,j}$, we do not use the original $H_{3,i}$, but the modified version obtained in the construction of $F'_{i,j-1}$. We then introduce the oriented spanning subgraph $H'_{3,i}$ of $H_{3,i}$ similarly as before (but with respect to the current 1-factor $F'_{i,j}$). Then all the above bounds on these graphs still hold, except that in the middle expression of (30) we multiply the term $6n/(\log n)^{1/5}$ by j to account for the total number of edges removed from $H_{3,i}$ so far. But this does not affect the next inequality. So eventually, all the $F'_{i,j}$ will satisfy (β_1)–(β_5).

5.7. **Merging the cycles in $F'_{i,j}$ to obtain Hamilton cycles.** Our final aim is to piece together the cycles in $F'_{i,j}$, for each i and j, to obtain edge-disjoint Hamilton cycles of G. Since we have ψ 1-factors $F'_{i,1}, \dots, F'_{i,\psi}$ for each G_i, in total we will find

$$\psi r' \overset{(27),(29)}{=} (1-2\gamma)\beta_2 m'(1-\gamma)L/\beta \overset{(26)}{\geq} (1-2\gamma)(1-\gamma)(1/2-\gamma)m'L \overset{(14)}{\geq} (1/2-\eta_1)n$$

edge-disjoint Hamilton cycles of G, as desired.

Recall that R' was defined in Section 5.1. Given any i, apply Lemma 21 to obtain a closed shifted walk

$$W_i = U_1^+ D_1' U_1 U_2^+ D_2' U_2 \dots U_{s-1}^+ D_{s-1}' U_{s-1} U_s^+ D_s' U_s U_1^+$$

in R' with respect to $\mathcal{F}_i$ such that each cycle in $\mathcal{F}_i$ is traversed at most $3L$ times. So $\{D_1', \dots, D_s'\}$ is the set of all cycles in $\mathcal{F}_i$, U_k^+ is the successor of U_k on D_k' and $U_k U_{k+1}^+ \in E(R')$ for each $k = 1, \dots, s$ (where $U_{s+1} := U_1$). Moreover,

$$s \leq 3L^2. \tag{31}$$

For each 1-factor $F'_{i,j}$ we will now use the edges of H_4 and $H_{5,i}$ to obtain a Hamilton cycle $C_{i,j}$ with the following properties:

(i) If $i \neq i'$ or $j \neq j'$ then $C_{i,j}$ and $C_{i',j'}$ are edge-disjoint.
(ii) $E(C_{i,j})$ consists of edges from $F'_{i,j}$, H_4 and $H_{5,i}$ only.
(iii) There are at most $3L^2$ edges from H_4 lying in $C_{i,j}$.
(iv) There are at most $3L^2 + 5$ edges from $H_{5,i}$ lying in $C_{i,j}$.

For each j, we will use W_i to 'guide' us how to merge the cycles in $F'_{i,j}$ into the Hamilton cycle $C_{i,j}$. Suppose that we have already defined $\ell < \psi r'$ of the Hamilton cycles $C_{i',j'}$ satisfying (i)–(iv), but have yet to define $C_{i,j}$. We remove all those edges which have been used in these ℓ Hamilton cycles from both H_4 and $H_{5,i}$.

For each $V \in V(\mathcal{F}_i)$, we denote by V_w the subcluster of V containing all those vertices which do not lie on a red edge in $F'_{i,j}$. We refer to V_w as the *white subcluster of* V. Thus $|V_w| \geq (1-c')m'$ by property (β_7) in Section 5.6. Note that the outneighbours of the vertices in V_w on $F'_{i,j}$ all lie in V^+ while their inneighbours lie in V^-. For each $k = 1, \dots, s$ we will denote the white subcluster of a cluster U_k by $U_{k,w}$. We use similar notation for U_k^+ and U_k^-.

Consider any $UV \in E(R')$. Recall that U and V are viewed as clusters of size m in R', but when considering $\mathcal{F}_i$ we are in fact considering subclusters of U and V of size m'. When viewed as clusters in R', UV initially corresponded to an ε-regular pair of density at least $\gamma_4 d'$ in H_4. Thus when viewed as clusters in $\mathcal{F}_i$, UV initially corresponded to a 2ε-regular pair of density at least $\gamma_4 d'/2$ in H_4. Moreover, initially the edges from U_w to V_w in H_4 induce a 3ε-regular pair of density at least $\gamma_4 d'/3$. However, we have removed all the edges lying in the ℓ Hamilton cycles $C_{i',j'}$

which we have defined already. Property (iii) implies that we have removed at most $3L^2\ell \leq 3L^2 n$ edges from H_4. Thus we have the following property:

(δ_1) Given any $UV \in E(R')$, let $S \subseteq U_w$, $T \subseteq V_w$ be such that $|S|, |T| \geq 3\varepsilon m'$. Then $e_{H_4}(S,T) \geq \gamma_4 d'|S||T|/4$.

When constructing $C_{i,j}$ we will remove at most $3L^2$ more edges from H_4. But since (δ_1) is far from being tight, it will hold throughout the argument below. Similarly, the initial definition of $H_{5,i}$ (c.f. Section 5.3) and (iv) together imply the following property:

(δ_2) Consider any edge $VV^+ \in E(\mathcal{F}_i)$. Let $S \subseteq V$ and $T \subseteq V^+$ be such that $|S|, |T| \geq \sqrt{\varepsilon} m'$. Then $e_{H_{5,i}}(S,T) \geq \gamma_5 \beta |S||T|/2$.

We now construct $C_{i,j}$ from $F'_{i,j}$. Condition (β_6) in Section 5.6 implies that, for each $k = 1, \dots, s$, every vertex in $V_G(D'_k)$ lies on the same cycle, C'_k say, in $F'_{i,j}$. Let $x_1 \in U_{1,w}$ be such that x_1 has at least $\gamma_4 d'|U^+_{2,w}|/4 \geq \gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{2,w}$. By (δ_1) all but at most $3\varepsilon m'$ vertices in $U_{1,w}$ have this property. Note that the outneighbour in $F'_{i,j}$ of any such vertex lies in U^+_1. However, by (δ_2) all but at most $\sqrt{\varepsilon} m'$ vertices in U^+_1 have at least $\gamma_5 \beta |U_{1,w}|/2 \geq \gamma_5 \beta m'/3$ inneighbours in $H_{5,i}$ which lie in $U_{1,w}$. Thus we can choose x_1 with the additional property that its outneighbour $y_1 \in U^+_1$ in $F'_{i,j}$ has at least $\gamma_5 \beta m'/3$ inneighbours in $H_{5,i}$ which lie in $U_{1,w}$.

Let P denote the directed path $C'_1 - x_1 y_1$ from y_1 to x_1. We now have two cases to consider.

Case 1. $C'_1 \neq C'_2$.

Note that x_1 has at least $\gamma_4 d'm'/5 - c'm' \gg \gamma_4 d'm'/6$ outneighbours $y'_2 \in U^+_{2,w}$ in H_4 such that the inneighbour of y'_2 in $F'_{i,j}$ lies in $U_{2,w}$. However, by (δ_1) all but at most $3\varepsilon m'$ vertices in $U_{2,w}$ have at least $\gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{3,w}$. Thus we can choose an outneighbour $y'_2 \in U^+_{2,w}$ of x_1 in H_4 such that the inneighbour x'_2 of y'_2 in $F'_{i,j}$ lies in $U_{2,w}$ and x'_2 has at least $\gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{3,w}$. We extend P by replacing it with $(P \cup C'_2 \cup \{x_1 y'_2\}) \setminus \{x'_2 y'_2\}$.

Case 2. $C'_1 = C'_2$.

In this case the vertices in $V_G(D'_2)$ already lie on P. We will use the following claim to modify P.

Claim 25. *There is a vertex $y_2 \in U^+_{2,w}$ such that:*

- *$x_1 y_2 \in E(H_4)$.*
- *The predecessor x_2 of y_2 on P lies in $U_{2,w}$.*
- *There is an edge $x_2 y'_2$ in $H_{5,i}$ such that $y'_2 \in U^+_{2,w}$ and y_2 precedes y'_2 on P (but need not be its immediate predecessor).*
- *The predecessor x'_2 of y'_2 on P lies in $U_{2,w}$.*
- *x'_2 has at least $\gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{3,w}$.*

Proof. Since x_1 has at least $\gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{2,w}$, at least $\gamma_4 d'm'/5 - c'm' - 3\varepsilon m' \geq \gamma_4 d'm'/6$ of these outneighbours y are such that the

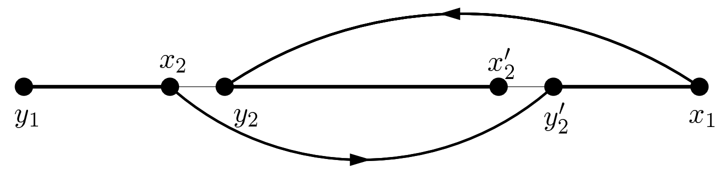

FIGURE 2. The modified path P in Case 2

predecessor x of y on P lies in $U_{2,w}$ and at least $\gamma_4 d'm'/5$ outneighbours of x in H_4 lie in $U^+_{3,w}$. This follows since all such vertices y have their predecessor on P lying in U_2 (since $y \in U^+_{2,w}$), since $|U_{2,w}| \geq (1-c')m'$ and since by (δ_1) all but at most $3\varepsilon m'$ vertices in $U_{2,w}$ have at least $\gamma_4 d'm'/5$ outneighbours in $U^+_{3,w}$. Let Y_2 denote the set of all such vertices y, and let X_2 denote the set of all such vertices x. So $|X_2| = |Y_2| \geq \gamma_4 d'm'/6$, $X_2 \subseteq U_{2,w}$, $Y_2 \subseteq U^+_{2,w} \cap N^+_{H_4}(x_1)$. Let X_2^* denote the set of the first $\gamma_4 d'm'/12$ vertices in X_2 on P and Y_2^* the set of the last $\gamma_4 d'm'/12$ vertices in Y_2 on P. Then (δ_2) implies the existence of an edge x_2y_2' from X_2^* to Y_2^* in $H_{5,i}$. Then the successor y_2 of x_2 on P satisfies the claim. □

Let x_2, y_2, x_2' and y_2' be as in Claim 25. We modify P by replacing P with

$$(P \cup \{x_1y_2, x_2y_2'\}) \backslash \{x_2y_2, x_2'y_2'\}$$

(see Figure 2).

In either of the above cases we obtain a path P from y_1 to some vertex $x_2' \in U_{2,w}$ which has at least $\gamma_4 d'm'/5$ outneighbours in H_4 lying in $U^+_{3,w}$. We can repeat the above process: If $C_3' \neq C_1', C_2'$ then we extend P as in Case 1. If $C_3' = C_1'$ or $C_3' = C_2'$ then we modify P as in Case 2. In both cases we obtain a new path P which starts in y_1 and ends in some $x_3' \in U_{3,w}$ that has at least $\gamma_4 d'm'/5$ outneighbours in H_4 lying in $U^+_{4,w}$. We can continue this process, for each C_k' in turn, until we obtain a path P which contains all the vertices in $C_1', \dots, C_s'$ (and thus all the vertices in G), starts in y_1 and ends in some $x_s' \in U_{s,w}$ having at least $\gamma_4 d'm'/5$ outneighbours in H_4 which lie in $U^+_{1,w}$.

Claim 26. *There is a vertex $y_1' \in U_1^+ \setminus \{y_1\}$ such that:*

- $x_s'y_1' \in E(H_4)$.
- *The predecessor x_1' of y_1' on P lies in $U_{1,w}$.*
- *There is an edge $x_1'y_1''$ in $H_{5,i}$ such that $y_1'' \in U^+_{1,w}$ and y_1' precedes y_1'' on P.*
- *The predecessor x_1'' of y_1'' on P lies in $U_{1,w}$.*
- *x_1'' has at least $\gamma_5\beta m'/3$ outneighbours in $H_{5,i}$ which lie in $U^+_{1,w}$.*

Proof. The proof is almost identical to that of Claim 25 except that we apply (δ_2) to ensure that x_1'' has at least $\gamma_5\beta m'/3$ outneighbours in $H_{5,i}$ which lie in $U^+_{1,w}$. □

Let x_1', y_1', x_1'' and y_1'' be as in Claim 26. We modify P by replacing it with the path

$$(P \cup \{x_s'y_1', x_1'y_1''\}) \backslash \{x_1'y_1', x_1''y_1''\}$$

from y_1 to x_1''. So P is a Hamilton path in G which is edge-disjoint from the ℓ Hamilton cycles $C_{i',j'}$ already defined. In each of the s steps in our construction of P we have added at most one edge from each of H_4 and $H_{5,i}$. So by (31) P contains at most $3L^2$ edges from H_4 and at most $3L^2$ edges from $H_{5,i}$. All other edges of P lie in $F'_{i,j}$. Recall that y_1 has at least $\gamma_5\beta m'/3$ inneighbours in $H_{5,i}$ which lie in $U_{1,w}$ and x_1'' has at least $\gamma_5\beta m'/3$ outneighbours in $H_{5,i}$ which lie in $U^+_{1,w}$. Thus we can apply Lemma 20 to $P \cup H_{5,i}$ with U_1^+ playing the role of V and U_1 playing the role of U to obtain a Hamilton cycle $C_{i,j}$ in G where $|E(C_{i,j})\backslash E(P)| \leq 5$. By construction, $C_{i,j}$ satisfies (i)–(iv). Thus we can indeed find $(1/2-\eta_1)n$ Hamilton cycles in G, as desired.

6. Almost decomposing oriented regular graphs with large semidegree

In this section, we describe how Theorem 3 can be extended to 'almost regular' oriented graphs whose minimum semidegree is larger than $3n/8$. More precisely, we say that an oriented graph G on n vertices is *$(\alpha \pm \eta)n$-regular* if $\delta^0(G) \geq (\alpha-\eta)n$ and $\Delta^0(G) \leq (\alpha+\eta)n$.

Theorem 27. *For every $\gamma > 0$ there exist $n_0 = n_0(\gamma)$ and $\eta = \eta(\gamma) > 0$ such that the following holds. Suppose that G is an $(\alpha \pm \eta)n$-regular oriented graph on $n \geq n_0$ vertices where $3/8+\gamma \leq \alpha < 1/2$. Then G contains at least $(\alpha-\gamma)n$ edge-disjoint Hamilton cycles.*

Theorem 27 is best possible in the sense that there are almost regular oriented graphs whose semidegrees are all close to $3n/8$ but which do not contain a Hamilton cycle. These were first found by Häggkvist [13]. However, we believe that if one requires G to be completely regular, then one can actually obtain a Hamilton decomposition of G. Note this would be a significant generalization of Kelly's conjecture.

Conjecture 28. *For every $\gamma > 0$ there exists $n_0 = n_0(\gamma)$ such that for all $n \geq n_0$ and all $r \geq (3/8+\gamma)n$ each r-regular oriented graph on n vertices has a decomposition into Hamilton cycles.*

At present we do not even have any examples to rule out the possibility that one can reduce the constant $3/8$ in the above conjecture:

Question 29. *Is there a constant $c < 3/8$ such that for every sufficiently large n every cn-regular oriented graph G on n vertices has a Hamilton decomposition or at least a set of edge-disjoint Hamilton cycles covering almost all edges of G?*

It is clear that we cannot take $c < 1/4$ since there are non-Hamiltonian k-regular oriented graphs on n vertices with $k = n/4-1/2$ (consider a union of 2 regular tournaments).

Sketch proof of Theorem 27. The proof of Theorem 27 is similar to that of Theorem 3. A detailed proof of Theorem 27 can be found in [31]. The main use of the assumption of high minimum semidegree in our proof of Theorem 3 was that for any pair A, B of large sets of vertices, we could assume the existence of many edges between A and B (see Lemma 14). This enabled us to prove the existence of very short paths, shifted walks and skeleton walks between arbitrary pairs of vertices. Lemma 14 does not hold under the weaker degree conditions of Theorem 27. However, (e.g. by Lemma 4.1 in [19]) these degree conditions are strong enough to imply the following 'expansion property': for any set S of vertices, we have that $|N^+_G(S)| \geq |S| + \gamma n/2$ (provided $|S|$ is not too close to n). Lemma 3.2 in [19] implies that this expansion property is also inherited by the reduced graph. So in the proof of Lemma 15, this expansion property can be used to find paths of length $O(1/\gamma)$ which join up given pairs of vertices. Similarly, in Lemma 21 we find closed shifted walks so that each cycle C in F is traversed $O(1/\gamma)$ times instead of just 3 times (such a result is proved explicitly in Corollary 4.3 of [19]). Finally, in the proof of Claim 23 we now find shadow skeleton walks whose length is $O(1/\gamma)$ instead of 5. In each of these cases, the increase in length does not affect the remainder of the proof. □

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