Subdivisions of a large clique in C_6-free graphs

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Abstract

Mader conjectured that every C_4-free graph has a subdivision of a clique of order linear in its average degree. We show that every C_6-free graph has such a subdivision of a large clique.

We also prove the dense case of Mader's conjecture in a stronger sense, i.e., for every c, there is a c' such that every C_4-free graph with average degree $cn^{1/2}$ has a subdivision of a clique K_ℓ with $\ell = \lfloor c'n^{1/2} \rfloor$ where every edge is subdivided exactly 3 times.

1 Introduction

A *subdivision* of a clique K_ℓ, denoted by TK_ℓ, is a graph obtained from K_ℓ by subdividing each of its edges into internally vertex-disjoint paths. Bollobás and Thomason [3], and independently Komlós and Szemerédi [14] proved the following celebrated result.

Theorem 1.1. *Every graph of average degree d contains a subdivision of a clique of order $\Omega(\sqrt{d})$.*

Theorem 1.1 is best possible: the disjoint union of $K_{d,d}$'s contains no subdivision of K_ℓ with $\ell \geq \sqrt{8d}$ (observed first by Jung [7]).

Mader [15] conjectured that if a graph is C_4-free, then one can find a subdivision of a much larger clique, of order linear in its average degree. Two major steps towards this conjecture were made by Kühn and Osthus: in [8], they showed that if the graph G has girth at least 15 and large average degree, then the conjecture is true in a stronger sense: a

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subdivision of $K_{\delta(G)+1}$ is guaranteed; in [9], they showed that one can find a subdivision of a clique of order almost linear, $\Omega(d/\log^{12} d)$, in any C_4-free graph with average degree d.

Extending ideas in [13] and [14], we prove that every C_6-free graph has such a subdivision of a large clique.

Theorem 1.2. *Let G be a C_6-free graph with average degree d. Then a TK_ℓ is a subgraph of G with $\ell = \lfloor cd \rfloor$ for some small positive constant c independent of d.*

Similar proof gives the following result, whose proof is omitted.

Theorem 1.3. *Let G be a C_{2k}-free graph with $k \geq 3$ and average degree d. Then a TK_ℓ is a subgraph of G with $\ell = \lfloor cd \rfloor$ for some small positive constant c independent of d.*

It is known that any C_4-free n-vertex graph has at most $O(n^{3/2})$ edges (see [12]). Our next result verifies the dense case of Mader's conjecture in a stronger sense.

Theorem 1.4. *For every $c > 0$ there is a $c' > 0$ such that the following holds. Let G be a C_4-free n-vertex graph with $cn^{3/2}$ edges. Then G contains a TK_ℓ with $\ell = \lfloor c'n^{1/2} \rfloor$, in which every edge of the K_ℓ is subdivided exactly 3 times.*

Theorem 1.4 can also be viewed as an extension of the following result of Alon, Krivelevich and Sudakov [1] for C_4-free graphs. Settling a question of Erdős [4], they showed, using the dependent random choice lemma, that if the average degree of a graph is of order $\Omega(n)$, then there is a TK_ℓ with $\ell = \Omega(n^{1/2})$, in which every edge of the K_ℓ is subdivided exactly once.

Notation: For a vertex v, denote by $S(v, i)$ the i-th sphere around v, i.e., the set of vertices of distance i from v and denote by $B(v, r)$ the ball of vertices of radius r around v, so $B(v, r) = \cup_{i \leq r} S(v, i)$. For a set $X \subseteq V(G)$, denote by $\Gamma(X)$ the external neighborhood of X, that is $\Gamma(X) := N(X) \setminus X$. Denote by $d(G)$ the average degree of G and for $S \subseteq V(G)$ denote by $d(S)$ the average degree of the induced subgraph $G[S]$. For a set of vertices S, denote by $N_i(S)$ the i-th common neighborhood of S, i.e., vertices of distance exactly i from every vertex in S. For a set $B \subseteq V(G)$, let $\Delta(B) := \max_{v \in B} d_G(v)$ and $\delta(B) := \min_{v \in B} d_G(v)$.

We will omit floors and ceilings signs when they are not crucial.

2 Preliminaries

For any graph G, there is a bipartite subgraph G' such that $e(G') \geq e(G)/2$. We shall use a result of Györi [6] which states that every bipartite C_6-free graph has a C_4-free subgraph with at least half of its edges. So having a loss of factor of 4 in the average degree, we may assume that our C_6-free graph is bipartite and also C_4-free. Following Komlós and Szemerédi [13], we introduce the following concept.

(ε_1, t)-expander: For $\varepsilon_1 > 0$ and $t > 0$, let $\varepsilon(x)$ be the function as follows:

$$\varepsilon(x) = \varepsilon(x, \varepsilon_1, t) := \begin{cases} 0 & \text{if } x < t/5 \\ \varepsilon_1 / \log^2(15x/t) & \text{if } x \geq t/5. \end{cases} \tag{1}$$

For the sake of brevity, on $\varepsilon(x)$ we do not write the dependency of ε_1 and t when it is clear from the context. Note that $\varepsilon(x)\cdot x$ is increasing for $x \geq t/2$. A graph G is an (ε_1, t)-*expander* if $|\Gamma(X)| \geq \varepsilon(|X|) \cdot |X|$ for all subsets $X \subseteq V$ of size $t/2 \leq |X| \leq |V|/2$.

Komlós and Szemerédi [13, 14] showed that every graph G contains an (ε, t)-expander that is almost as dense as G.

Theorem 2.1. *Let $t > 0$, and choose $\varepsilon_1 > 0$ sufficiently small (independent of t) so that $\varepsilon = \varepsilon(x)$ defined in (1) satisfies $\int_1^\infty \frac{\varepsilon(x)}{x} dx < \frac{1}{8}$. Then every graph G has a subgraph H with $d(H) \geq d(G)/2$ and $\delta(H) \geq d(H)/2$, which is an (ε_1, t)-expander.*

Remark: The subgraph H might be much smaller than G. For example if G is a vertex-disjoint collection of K_{d+1}'s, then H will be just one of the K_{d+1}'s.

We will use the following version of Theorem 2.1.

Corollary 2.2. *There exists ε_0 with $0 < \varepsilon_0 < 1$ such that for every $0 < \varepsilon_1 \leq \varepsilon_0$, $\varepsilon_2 > 0$ and every graph G, there is a subgraph $H \subseteq G$ with $d(H) \geq d(G)/2$ and $\delta(H) \geq d(H)/2$ which is an $(\varepsilon_1, \varepsilon_2 d(H)^2)$-expander.*

Proof. Let $G' \subseteq G$ be a subgraph maximizing $d(G')$ and define $t' := \varepsilon_2 d(G')^2/4$. If ε_0 is sufficiently small, then for any $\varepsilon_1 \leq \varepsilon_0$, applying Theorem 2.1 yields a $(4\varepsilon_1, t')$-expander $H \subseteq G'$ with $d(G')/2 \leq d(H) \leq d(G')$ and $\delta(H) \geq d(H)/2$. Define $t := \varepsilon_2 d(H)^2$. Since $d(G')/2 \leq d(H) \leq d(G')$, we have $t' \leq t \leq 4t'$. A simple calculation shows that for every $x \geq t/2$,

$$\frac{4\varepsilon_1}{\log^2(15x/t')} \geq \frac{\varepsilon_1}{\log^2(15x/t)}.$$

Hence H is an (ε_1, t)-expander as desired. $\square$

Every (ε_1, t)-expander graph has the following robust "small diameter" property (see Corollary 2.3 in [14]):

Corollary 2.3. *If G is an (ε_1, t)-expander, then any two vertex sets, each of size at least $x \geq t$, are of distance at most*

$$diam := diam(n, \varepsilon_1, t) = \frac{2}{\varepsilon_1} \log^3(15n/t),$$

and this remains true even after deleting $x\varepsilon(x)/4$ arbitrary vertices from G.

By Corollary 2.2, we may assume, when proving Theorem 1.2, that G is a bipartite, $\{C_4, C_6\}$-free, (ε_1, t)-expander graph with average degree d, $\delta(G) \geq d/2$ and $t = \varepsilon_2 d^2$ for some $\varepsilon_1 \leq \varepsilon_0$ and $\varepsilon_2 > 0$. Indeed, instead of G we might work in a still dense subgraph H of it, having the properties listed before and by resetting $d := d(H) \geq d(G)/2$ it suffices to find in H a TK_ℓ with $\ell = \Omega(d(H))$. The next lemma finds in G a "nice" subgraph with "bounded" maximum degree.

Lemma 2.4. *Let $0 < \varepsilon_1 < 1$ and $\varepsilon_2 > 0$. Let G be an n-vertex bipartite, C_4-free, $(\varepsilon_1, \varepsilon_2 d^2)$-expander graph with average degree d and $\delta(G) \geq d/2$. Then either G contains a subdivision of a clique of order linear in d, or G has a C_4-free subgraph G' with average degree $d(G') \geq d/2$ and $\delta(G') \geq d(G')/4$, that is $(\varepsilon_1/8, 4\varepsilon_2 d(G')^2)$-expander. Furthermore, G' has at least $n/2$ vertices and $\Delta(G') \leq d(G') \log^8(|V(G')|/d(G')^2)$.*

Note that we do not use the C_6-freeness of G in Lemma 2.4. Using Lemma 2.4, to prove Theorem 1.2, it will be sufficient to show Theorem 2.5 below.

Theorem 2.5. *Let $0 < \varepsilon_1 \leq \varepsilon_0$ and $\varepsilon_2 > 0$, where ε_0 is the constant from Corollary 2.2. Let G be an n-vertex bipartite, $\{C_4, C_6\}$-free, $(\varepsilon_1, \varepsilon_2 d^2)$-expander graph with average degree d, $\delta(G) \geq d/4$ and $\Delta(G) \leq d \log^8 n$. Then G contains a $TK_{\ell/2}$ for $\ell = cd$ for some constant $c > 0$ independent of d.*

We will need the following "independent bounded differences inequality" (see [16]).

Theorem 2.6. *Let $\mathbf{X} = (X_1, X_2, \ldots, X_n)$ be a family of independent random variables with X_k taking values in a set A_k for each k. Suppose that the real-valued function f defined on $\prod A_k$ satisfies $|f(\mathbf{x}) - f(\mathbf{x}')| \leq \sigma_k$ whenever the vectors $\mathbf{x}$ and $\mathbf{x}'$ differ only in the k-th coordinate. Let μ be the expected value of the random variable $f(\mathbf{X})$. Then for any $t \geq 0$,*

$$\mathbb{P}(|f(\mathbf{X}) - \mu| \geq t) \leq 2e^{-2t^2/\sum \sigma_k^2}.$$

The rest of the paper will be organized as follows: The proof of Lemma 2.4 will be given in Section 3 as well as the reduction of Theorem 1.2 to Theorem 2.5. The proof of Theorem 2.5 will be divided into two parts according to the range of d: the dense case when $d \geq \log^{14} n$ will be handled in Section 4, and the sparse case when $d < \log^{14} n$ in Section 5. The proof of Theorem 1.4 will be given in Section 6. In Section 7, we will give some concluding remarks.

3 Reduction to "bounded" maximum degree

Let G be an n-vertex bipartite C_4-free $(\varepsilon_1, \varepsilon_2 d^2)$-expander graph with average degree d and $\delta(G) \geq d/2$.

In this section, we will show that we can transform G into a subgraph G' with $d(G') \geq d/2$, $\delta(G') \geq d(G')/4$ and $\Delta(G') \leq d(G') \log^8(|V(G')|/d(G')^2)$, where G' is an $(\varepsilon_1/8, 4\varepsilon_2 d(G')^2)$-expander. For simplicity, throughout this section, define

$$t := \varepsilon_2 d^2 \qquad \text{and} \qquad t' := 4\varepsilon_2 d(G')^2.$$

To prove Lemma 2.4, we shall use the following two lemmas: Lemmas 3.1 and 3.2.

Choose a constant $c < \frac{1}{24000}$ such that $c \ll \varepsilon_1$. Set the parameters as follows:

$$\ell = cd, \quad m = \log \frac{15n}{t}, \quad \Delta = \frac{dm^8}{600}, \quad \Delta' = dm^4, \quad \varepsilon(n, \varepsilon_1, t) = \frac{\varepsilon_1}{m^2}, \quad diam = \frac{2m^3}{\varepsilon_1}.$$

Note that d has to be sufficiently large (say $d > 1/c$) so that $\ell \geq 1$.

If $m \leq 1/c^2$, then $d \geq e^{-1/2c^2} n^{1/2}$, and we can apply Theorem 1.4 to get a subdivision of a clique of order linear in d. Thus we may assume that $1/m \ll c \ll \varepsilon_1$. By the same argument, we may also assume that $d\Delta \leq n$ and $n/d^2 \gg 1/\varepsilon_2$.

Let $L \subseteq V(G)$ be the set of all vertices of degree at least Δ.

Lemma 3.1. *We can find in G either a $TK_{\ell/2}$, or $|L| \leq \ell$ and $G' := G[V \setminus L]$ has maximum degree at most Δ.*

Proof. Indeed, if $|L| \geq \ell$, then we can choose a subset $L' \subseteq L$ of exactly ℓ vertices, say $L' := \{v_1, \ldots, v_\ell\}$. We shall build a copy of $TK_{\ell/2}$ using a subset of these high-degree vertices from L' as core vertices.

First we choose for each vertex v_i, $S_1(v_i) \subseteq S(v_i, 1)$ and $S_2(v_i) \subseteq S(v_i, 2)$ such that:

(i) all $S_1(v_i)$'s are pairwise disjoint, and each $S_1(v_i)$ is disjoint from L' and of size $\Delta/2$;

(ii) every $S_2(v_i)$ is disjoint from $\bigcup_{j=1}^{\ell} S_1(v_j) \cup L'$, and each $S_2(v_i)$ is of size $d\Delta/5$;

(iii) for every $1 \leq i \leq \ell$, each vertex in $S_1(v_i)$ has at most $d/2$ neighbors in $S_2(v_i)$.

We can indeed select such sets:

For (i), since G is C_4-free, for any v_i, every other v_j with $j \neq i$ has at most one neighbor in $S(v_i, 1)$. Since $|S(v_i, 1)| - 2\ell \geq \Delta - 2\ell \geq \Delta/2$, we can remove these neighbors of v_j's and L' from $S(v_i, 1)$ and then choose exactly $\Delta/2$ vertices for $S_1(v_i)$.

For (ii) and (iii), recall that G is bipartite and $\delta(G) \geq d/2$. Thus we can choose, for each vertex in $S_1(v_i)$, exactly $d/2 - 1$ vertices in $S(v_i, 2)$. Since G is C_4-free, for a given v_i, all chosen vertices should be distinct. Thus we have chosen at least $(d/2 - 1)(\Delta/2) \geq 100\ell\Delta \geq 100 \left|\bigcup_{j=1}^{\ell} S_1(v_j)\right|$ vertices, simply discard those vertices which are in $\bigcup_{j=1}^{\ell} S_1(v_j) \cup L'$ and then choose $d\Delta/5$ vertices for $S_2(v_i)$. Clearly $S_2(v_i)$ satisfies both (ii) and (iii).

We now describe the greedy algorithm that we use to connect the vertices v_i's. Denote by $B_1(v_i) := S_1(v_i) \cup \{v_i\}$ and by $B_2(v_i) := B_1(v_i) \cup S_2(v_i)$.

Greedy Algorithm: We try to connect these ℓ core vertices pair by pair in an arbitrary order. For the current pair of core vertices v_i, v_j, we try to connect $B_2(v_i)$ and $B_2(v_j)$ using a shortest path of length at most *diam* and then exclude all the internal vertices in this path from further connections. We need to justify that such a short path exists.

Suppose we have already connected some pairs using paths of length at most *diam*. We will exclude all previously used vertices from $B_1(v_i) \cup B_1(v_j)$ and also those vertices from $S_2(v_i)$, $S_2(v_j)$ adjacent to removed vertices from $S_1(v_i)$ or $S_1(v_j)$. Formally, let U be the set of vertices used in previous connections and denote by $U_i := U \cap S_1(v_i)$ and by $U_j := U \cap S_1(v_j)$. Define $N := (\Gamma(U_i) \cap S_2(v_i)) \cup (\Gamma(U_j) \cap S_2(v_j))$. Then the set of vertices excluded is $U \cup N$. First we bound the size of U, it is at most

$$\ell^2 \cdot diam \leq c^2 d^2 \cdot \frac{2m^3}{\varepsilon_1} \leq c d^2 m^3,$$

as there are at most ℓ^2 pairs of core vertices and for each connection, the length of a path is bounded by *diam*.

Call a core vertex v_i bad, if more than Δ' vertices from $S_1(v_i)$ are used in previous connections. During the connections, we discard a core vertex when it becomes bad. We discard in total at most $\ell/2$ core vertices. Indeed, we have used at most $\ell^2 \cdot diam$ vertices. Since by (i), $S_1(v_i)$'s are pairwise disjoint, each bad core vertex, by definition, uses at least Δ' of them. Thus the number of discarded bad core vertices is at most

$$\frac{\ell^2 \cdot diam}{\Delta'} \le \frac{cd^2m^3}{dm^4} = \frac{cd}{m} \ll \frac{\ell}{2}.$$

Hence there are at least $\ell/2$ core vertices survive the entire process.

Recall that by (iii), each vertex in U_i (or U_j resp.) has at most $d/2$ neighbors in $S_2(v_i)$ (or $S_2(v_j)$ resp.). Note that every survived core vertex is not bad, namely $|U_i| \le \Delta'$. Thus $|N| \le \Delta' \cdot d/2 = d^2m^4/2$. Hence the total number of vertices we exclude from $B_2(v_i)$ (or $B_2(v_j)$ resp.) is at most

$$\ell^2 \cdot diam + |N| \le cd^2m^3 + \frac{1}{2}d^2m^4 \le d^2m^4.$$

After excluding these vertices, we still have at least

$$|S_2(v_i)| - \ell^2 \cdot diam - |N| \ge \frac{d\Delta}{5} - d^2m^4 \ge \frac{d\Delta}{10}$$

vertices left in $S_2(v_i)$, the same holds for $S_2(v_j)$. Recall that, when $x \ge t/2$, $\varepsilon(x, \varepsilon_1, t)$ is decreasing and $x\varepsilon(x, \varepsilon_1, t)$ is increasing. So we have that the number of vertices we are allowed to exclude, by Corollary 2.3, is at least

$$\frac{1}{4} \cdot \frac{d\Delta}{10} \cdot \varepsilon\left(\frac{d\Delta}{10}, \varepsilon_1, t\right) \ge \frac{d\Delta}{40} \cdot \varepsilon(n, \varepsilon_1, t) \ge \frac{d^2m^8}{24000} \cdot \frac{\varepsilon_1}{m^2} = \frac{\varepsilon_1 d^2 m^6}{24000} \gg d^2m^4,$$

where the last inequality follows from $1/m \ll c \ll \varepsilon_1$ and $c < \frac{1}{24000}$. Thus the exclusion of these vertices will not affect the robust small diameter property between $B_2(v_i)$'s. So the $\ell/2$ remaining core vertices can be connected to form a $TK_{\ell/2}$. □

Given that c is sufficiently small and now we can assume $|L| \le \ell$, we have that $|V(G')| \ge n - \ell \ge n/2$. Note that $d(G') \ge \frac{2(dn/2 - \ell n)}{n} = d - 2\ell \ge d/2$, thus $t' \ge t$. On the other hand, $G' = G[V \setminus L]$ and L consists of vertices of degree at least $\Delta \gg d$, thus $d(G') \le \frac{nd - |L|\Delta/2}{n - |L|} \le d$. Hence $t' \le 4t$ and $\delta(G') \ge \delta(G) - \ell \ge d/2 - \ell \ge d(G')/4$.

Lemma 3.2. *The obtained graph G' is an $(\varepsilon_1/8, t')$-expander.*

Proof. Recall that $t \le t' \le 4t$. Since G is an (ε_1, t)-expander, for any set X in G' of size $x \ge t'/2 \ge t/2$, it is easy to check that

$$\begin{aligned} |\Gamma_G(X)| &\ge x \cdot \varepsilon(x, \varepsilon_1, t) = x \cdot \frac{\varepsilon_1}{\log^2(15x/t)} \ge x \cdot \frac{\varepsilon_1/4}{\log^2(15x/t')} = x \cdot \varepsilon(x, \varepsilon_1/4, t') \\ &\ge \frac{t'}{2} \cdot \varepsilon\left(\frac{t'}{2}, \frac{\varepsilon_1}{4}, t'\right) = \frac{\varepsilon_1 t'}{8\log^2(7.5)} \gg \ell \ge |L|. \end{aligned}$$

Hence $|\Gamma_{G'}(X)| \ge |\Gamma_G(X)| - |L| \ge x\varepsilon(x, \varepsilon_1/4, t') - \ell \ge \frac{1}{2}x\varepsilon(x, \varepsilon_1/4, t') = x\varepsilon(x, \varepsilon_1/8, t')$. □

Recall that $1/\varepsilon_2 \ll n/d^2 \leq 2|V(G')|/d(G')^2$, the maximum degree of G' is at most

$$\Delta = \frac{dm^8}{600} \leq \frac{d(G')}{300} \cdot \log^8 \frac{30|V(G')|}{\varepsilon_2 d(G')^2} \leq \frac{d(G')}{300}\left(2\log\frac{|V(G')|}{d(G')^2}\right)^8 \leq d(G')\log^8\frac{|V(G')|}{d(G')^2}.$$

Slightly abusing the notation, we work in the future only with G'. We will rename G' as G, relabelling $n = |V(G')|$ and $d = d(G')$, and by changing ε_1 to $\varepsilon_1/8$ and ε_2 to $4\varepsilon_2$, we assume that G is $(\varepsilon_1, \varepsilon_2 d^2)$-expander and its maximum degree is at most $d\log^8(n/d^2)$. This completes the reduction step, i.e., to prove Theorem 1.2 it is sufficient to prove Theorem 2.5.

4 Dense case of Theorem 2.5

In this section, we prove the following lemma, which covers the dense case of Theorem 2.5.

Lemma 4.1. *Let $0 < \varepsilon_1 \leq \varepsilon_0$ and $\varepsilon_2 > 0$, where ε_0 is the constant from Corollary 2.2. Let G be an n-vertex bipartite, $\{C_4, C_6\}$-free, $(\varepsilon_1, \varepsilon_2 d^2)$-expander graph with average degree $d \geq \log^{14} n$, $\delta(G) \geq d/4$ and $\Delta(G) \leq d\log^8 n$. Then G contains a $TK_{\ell/2}$ for $\ell = cd$ for some constant $c > 0$ independent of d.*

Let G be a graph satisfying the conditions in Lemma 4.1. Choose a constant $c > 0$ such that $c \ll \varepsilon_1$ and set $\ell = cd$. In addition, set the parameters in this section as follows:

$$\Delta = d\log^8 n, \quad \Delta'' = d\log^{13} n, \quad b = \frac{d}{\log^9 n}, \quad diam = \frac{2}{\varepsilon_1}\log^3\left(\frac{15n}{\varepsilon_2 d^2}\right) \leq \frac{1}{c}\log^3 n.$$

Note that $\Delta \gg d \gg b$, $\Delta'' = o(d^2)$, and $\ell/b \leq d/b = \log^9 n$.

We will first find ℓ vertices, $v_1, \ldots, v_\ell$ serving as core vertices, along with some sets $B_3(v_i) \subseteq B(v_i, 3)$. We then connect all core vertices by linking $B_3(v_i)$'s using a greedy algorithm. Similarly to the proof in Section 3, we might discard few core vertices during the process.

4.1 Choosing core vertices and building $B_3(v_i)$

We will select ℓ vertices $v_1, \ldots, v_\ell$ in ℓ/b steps to serve as core vertices.

Stage 1: We choose core vertices $v_1, \ldots, v_\ell$ and the sets $B_2(v_i)$'s.

In each step, we choose a block of vertices consisting of: b core vertices and for each core vertex v_i a set $B_2(v_i) := S_1(v_i) \cup S_2(v_i) \cup \{v_i\}$, where $S_1(v_i) \subseteq S(v_i, 1)$ and $S_2(v_i) \subseteq S(v_i, 2)$ with the following properties:

(i) $S_1(v_i)$'s are pairwise disjoint for all $1 \leq i \leq \ell$ and $|S_1(v_i)| = d/2$.
(ii) For every i, $|S_2(v_i)| = d^2/10$.
(iii) Every vertex $w \in S_1(v_i)$ has at most $d/4$ neighbors in $S_2(v_i)$.
(iv) Inside each block, the sets $B_2(v_i)$'s are pairwise disjoint.
(v) Every $S_2(v_i)$ is disjoint from $\cup_{j=1}^{\ell} S_1(v_j)$.

(vi) For every $i \neq j$, $v_i \notin B_2(v_j)$.

To achieve this, we first choose a core vertex v_i with sets $S_1(v_i)$ of size $d/2$ and $S_2'(v_i) \subseteq S(v_i, 2)$ of size $d^2/8 - d/2$ for all $i \leq \ell$. We then choose $S_2(v_i) \subseteq S_2'(v_i)$. Suppose we have chosen some core vertices $v_1, v_2, \dots, v_{i-1}$ and sets $S_1(v_j)$ and $S_2'(v_j)$'s for $j \leq i-1$. Denote by D the current block and let $B_1(v_j) := S_1(v_j) \cup \{v_j\}$, $j \leq i-1$. To choose the next core vertex v_i, we will exclude $\{\bigcup_{j \leq i-1} B_1(v_j)\} \cup \{\bigcup_{v_k \in D} S_2'(v_k)\}$. The number of excluded vertices is at most

$$\sum_{j \leq i} |B_1(v_j)| + b \cdot \max_{v_k \in D} |S_2'(v_k)| \leq \ell d + b \cdot d^2/2 \leq b \cdot d^2.$$

The number of the edges incident to the excluded vertices is at most

$$\Delta \cdot b \cdot d^2 = \frac{d^4}{\log n} \ll \frac{dn}{2} = e(G),$$

the last inequality holds since G is C_6-free and therefore $d = O(n^{1/3})$ (see [2]). Thus, we can easily find in G, excluding these vertices, a subgraph G' with average degree at least $d/2$ and minimum degree at least $d/4$. We then choose v_i to be any vertex in G' of degree at least $d/2$. Choose $d/2$ neighbors of v_i to be $S_1(v_i)$. Since G is bipartite, for each vertex $u \in S_1(v_i)$, we can choose $d/4 - 1$ neighbors of u not in $B_1(v_i)$. Again, by C_4-freeness, we have chosen $d^2/8 - d/2$ different vertices. Denote the resulting set $S_2'(v_i)$. Note that in the process above, for any $i > j$, the set $S_1(v_i)$ is chosen after $S_2'(v_j)$. Thus when choosing $S_1(v_i)$, vertices in $S_2'(v_j)$ could be included if v_i is in a different block from v_j. Since $|S_2'(v_i) \setminus \cup_{j \leq \ell} S_1(v_j)| \geq |S_2'(v_i)| - \ell \cdot d \geq d^2/10$, we choose a subset of $S_2'(v_i) \setminus \cup_{j \leq \ell} S_1(v_j)$ of size exactly $d^2/10$ to be $S_2(v_i)$.

Stage 2: For each $1 \leq i \leq \ell$, choose $S_3(v_i)$ of size $d^3/50$ and $B_3(v_i)$.

For each vertex in $S_2(v_i)$, since G is bipartite and C_4-free, we can choose $d/4 - 1$ of its neighbors not in $S_1(v_i) \cup S_2(v_i)$ and denote the resulting set $S_3'(v_i)$. Since G is C_6-free, $|S_3'(v_i)| = |S_2(v_i)| \cdot (d/4 - 1) = d^3/40 - d^2/10$. Delete from $S_3'(v_i)$ any vertex in $\bigcup_{1 \leq j \leq \ell} B_1(v_j)$. Since we delete at most d^2 vertices, we can choose a subset of size $d^3/50$ to be $S_3(v_i)$. Let $B_3(v_i) := B_2(v_i) \cup S_3(v_i)$.

4.2 Connecting core vertices

Greedy Algorithm: Now we will connect the ℓ core vertices pair by pair in an arbitrary order. For each pair v_i and v_j, we will connect them with a path of length at most *diam* avoiding $\bigcup_{p \neq i,j} B_1(v_p)$.

(I) Discard bad core vertices:

Call a core vertex v_i bad, if we use more than Δ'' vertices from $S_2(v_i)$. Discard a core vertex as soon as it becomes bad. During the entire process, we use at most $\ell^2 \cdot diam$ vertices from previous connections. Since $B_2(v_i)$'s are pairwise disjoint inside each block, each of the excluded vertices can appear in at most ℓ/b many $S_2(v_i)$'s. Hence, the number of bad core vertices is at most:

$$\frac{\ell^2 \cdot diam \cdot (\ell/b)}{\Delta''} \leq \frac{d^2 \cdot diam \cdot (\ell/b)}{d \log^{13} n} \leq \frac{d \log^3 n \cdot \ell}{cb \log^{13} n} = \frac{\ell}{c \log n} \ll \ell/2.$$

(II) Cleaning before connection:

Assume that we have already connected some pairs of core vertices, and now we want to connect v_i and v_j. Before we start connecting them, clean $B_3(v_i)$ (do the same for $B_3(v_j)$) in the following way. Notice that we have used in previous connections at most ℓ vertices in $S_1(v_i)$, at most Δ'' vertices in $S_2(v_i)$ and at most $\ell^2 \cdot diam$ vertices in $S_3(v_i)$, since vertices in $S_1(v_i)$ were only used when connecting v_i to other core vertices and v_i is not bad. Also, delete those vertices that are no longer available, i.e., those adjacent to used ones. Call the resulting set $B_3'(v_i)$. Since every vertex in $S_k(v_i)$ for $k \in \{1, 2\}$ has at most $d/4$ neighbors in $S_{k+1}(v_i)$, we have deleted at most $\ell(1 + d/4 + d^2/16) + \Delta''(1 + d/4) + \ell^2 \cdot diam \ll d^3/100$ vertices. Thus $|B_3'(v_i)| \geq |B_3(v_i)| - d^3/100 \geq d^3/100$.

(III) Connecting core vertices:

We will connect v_i and v_j by a shortest path from $B_3'(v_i)$ to $B_3'(v_j)$ avoiding $\bigcup_{p \neq i,j} B_1(v_p)$ which is of size at most d^2. This path has length at most $diam$ if we do not break the robust diameter property. We then exclude this path for further connections. The number of excluded vertices from previous paths and from $\bigcup_{p \neq i,j} B_1(v_p)$ is at most $\ell^2 \cdot diam + d^2 \leq d^2 \log^3 n$. On the other hand, the number of vertices we are allowed to exclude without breaking the robust small diameter among $B_3'(v_i)$'s is

$$\frac{1}{4}|B_3'(v_i)|\varepsilon(|B_3'(v_i)|) \geq \frac{d^3}{400}\varepsilon(n) \geq \frac{\varepsilon_1 d^3}{400 \log^2 n} \gg d^2 \log^3 n.$$

Thus the robust diameter property is guaranteed during the entire process.

This completes the proof of Lemma 4.1, hence the dense case of Theorem 2.5.

5 Sparse case of Theorem 2.5

In this section, we will prove the sparse case of Theorem 2.5. Throughout this section G will be a sparse graph satisfying the conditions in Theorem 2.5, i.e., an n-vertex bipartite $\{C_4, C_6\}$-free $(\varepsilon_1, \varepsilon_2 d^2)$-expander graph, with average degree $d \leq \log^{14} n$, $\delta(G) \geq d/4$ and $\Delta(G) \leq d \log^8 n$. We always use n for $|V(G)|$ and d for $d(G)$. Inspired by an idea from [11] together with a random sparsening trick, we will show that in the sparse case, either we can find in G a 1-subdivision (i.e., each edge is subdivided once) of some graph H with $d(H) = \Omega(d^2)$, or there is a sparse and "almost regular" expander subgraph G_1 in G. In the first case, we apply Theorem 1.1 to find a subdivision of K_ℓ in H, hence in G, with $\ell = \Omega(\sqrt{d(H)}) = \Omega(d)$. For the second case, we use the following result of Komlós and Szemerédi (Theorem 3.1 in [13]).

Theorem 5.1. *If F is an $(\varepsilon_1, d(F))$-expander satisfying $d(F)/2 \le \delta(F) \le \Delta(F) \le 72(d(F))^2$ and $d(F) \le \exp\{(\log |V(F)|)^{1/8}\}$, then F contains a copy of TK_ℓ with $\ell = \Omega(d(F))$.*

The following lemma will be useful.

Lemma 5.2. *Let $F = (X \cup Y, E)$ be a bipartite C_4-free graph. If $|X| = \Omega(d^2|Y|)$ and $\frac{e(F)}{|X|} = \Omega(\Delta(X))$, then F contains a copy of TK_ℓ with $\ell = \Omega(d)$.*

Proof. In F, we call a path of length 2 with endpoints in Y a *hat*. By the convexity of the function $f(x) = \binom{x}{2}$, we have that the total number of hats in F is at least

$$\sum_{v \in X} \binom{\deg(v)}{2} \ge \frac{|X|}{3} \cdot \left(\frac{e(F)}{|X|}\right)^2.$$

By the pigeonhole principle, there exists a collection of hats $\mathcal{H}$ with distinct midpoints of size

$$|\mathcal{H}| \ge \frac{|X|}{3(\Delta(X))^2} \cdot \left(\frac{e(F)}{|X|}\right)^2 = \Omega(|X|) = \Omega(d^2|Y|).$$

Define a graph H on vertex set Y, where two vertices $y, y' \in Y$ are adjacent if there is a hat in $\mathcal{H}$ with y, y' as endpoints. Note that since F is C_4-free, any two hats have different sets of endpoints. Hence, each hat in $\mathcal{H}$ gives rise to a distinct edge in H. Thus

$$d(H) = \frac{2e(H)}{|Y|} = \frac{2|\mathcal{H}|}{|Y|} = \Omega(d^2).$$

Since the hats in $\mathcal{H}$ have distinct midpoints, there is a 1-subdivision of H in F with core vertices in Y and hats in $\mathcal{H}$ served as subdivided edges. We then apply Theorem 1.1 to find a subdivision of K_ℓ in H, hence in F, with $\ell = \Omega(\sqrt{d(H)}) = \Omega(d)$. $\square$

Let $B := \{v \in V(G) : \deg_G(v) \ge d^3\}$ and $A := V(G) \setminus B$. Note that $|B| \le \frac{d \cdot |V(G)|}{d^3} = \frac{n}{d^2}$, hence $|A| = |V(G)| - |B| \ge \frac{9n}{10}$. We first show that we may assume that there is a $G' \subseteq G$ with $|V(G')| = \Omega(n)$, $d(G') = \Theta(d)$ and $\Delta(G') \le d^3$.

Lemma 5.3. *We can find in G either a TK_ℓ with $\ell = \Omega(d)$, or there is a $G' \subseteq G$ with $|V(G')| \ge 9n/10$, $d/20 \le d(G') \le d$ and $\Delta(G') \le d^3$. In the later case, there is a set $A' \subseteq V(G')$ such that $|A'| \ge |V(G')|/2$ and for any $v \in A'$, $\deg_{G'}(v) \ge d/10$.*

Proof. Define $G' := G[A]$, $A' := \{v \in A : \deg_{G'}(v) \ge d/10\}$ and $A'' := A \setminus A'$. We distinguish two cases based on the sizes of A' and A''.

Case 1: Assume $|A''| \ge |A|/2$. Then $|A''| \ge 9n/20 = \Omega(d^2|B|)$. Note that, by the definition of A'', for any $a \in A''$, we have $\deg_{G[A'',B]}(a) \ge \delta(G) - \deg_{G'}(a) \ge d/4 - d/10 \ge d/10$. We bound in $G[A'', B]$ the degree of vertices in A'' as follows: for each $a \in A''$ with more than d edges to B, keep exactly d of them and delete the rest. Let the resulting graph be G''. Then in G'', $\Delta(A'') \le d$, hence $\frac{e(G'')}{|A''|} \ge \delta(A'') \ge d/10 = \Omega(\Delta(A''))$. Applying Lemma 5.2 to G'' gives the first alternative of the conclusion of Lemma 5.3.

Case 2: Assume $|A'| \geq |A|/2$. The graph G' was obtained from G by removing vertices of degree at least d^3 (which were in B), thus $d(G') \leq d$. On the other hand, by the definition of A', we have $d(G') \geq \frac{|A'| \cdot d/10}{|A|} \geq d/20$ and $\Delta(G') \leq d^3$ as desired. $\square$

From now on, we will work only in $G' = G[A]$ with the properties listed in Lemma 5.3. For the rest of the proof in this section, we fix sufficiently large constants $C' \ll C \ll K$ and a small constant $c_0 \leq \frac{1}{1000}$.

Let $W := \{v \in V(G') : \deg_{G'}(v) \geq c_0 d^2\}$, and $U := V(G') \setminus W$. Note that $|W| \leq \frac{d(G') \cdot |V(G')|}{c_0 d^2} \leq \frac{n}{c_0 d}$, hence $|U| = |A| - |W| \geq \frac{4n}{5}$.

Lemma 5.4. *We can find in G' either a TK_ℓ with $\ell = \Omega(d)$, or there exist vertex sets $U_0 \subseteq U$ and $W_0 \subseteq W$ with $|U_0| \geq |U|/6$ and $|W_0| \leq 2C|W|/d$ such that $G'[U_0, W_0]$ has at least $C'|U_0|$ edges and every vertex in U_0 has degree at most K in $G'[U_0, W_0]$.*

We first show how Lemma 5.4 completes the proof of the sparse case of Theorem 2.5. Let U_0, W_0 be sets with properties listed in Lemma 5.4. Note that $|U_0| = \Omega(d^2|W_0|)$. Denote by $G_0 := G'[U_0, W_0]$. Recall that $\Delta(U_0) = K = O(1)$, thus $\frac{e(G_0)}{|U_0|} \geq C' = \Omega(\Delta(U_0))$. Applying Lemma 5.2 to G_0 gives a copy of TK_ℓ with $\ell = \Omega(d)$. This completes the proof of the sparse case of Theorem 2.5.

Proof of Lemma 5.4. Recall that $A' \subseteq V(G')$ consists of vertices of degree at least $d/10$ in G'. Define $U' := \{v \in A' \cap U : \deg_{G'[U,W]}(v) \geq d/20\}$ and $U'' := \{A' \cap U\} \setminus U'$. By Lemma 5.3, $|A'| \geq \frac{|V(G')|}{2} = \frac{|U|+|W|}{2}$. Thus $|U'| + |U''| = |A' \cap U| \geq |A'| - |W| \geq \frac{|U|-|W|}{2} \geq \frac{2|U|}{5}$. We distinguish two cases based on the sizes of U' and U''.

Case 1: $|U''| \geq |U|/5$. Note that for every $v \in U''$, by the definition of U'',

$$\deg_{G'[U]}(v) = \deg_{G'}(v) - \deg_{G'[U,W]}(v) \geq \frac{d}{10} - \frac{d}{20} = \frac{d}{20}.$$

Thus $d(G'[U]) \geq \frac{d/20 \cdot |U''|}{|U|} \geq d/100$ and by the definition of U we have $\Delta(G'[U]) \leq c_0 d^2$. Then we apply Corollary 2.2 to $G'[U]$ and let G_1 be the resulting $(\varepsilon_1, \varepsilon_2 d(G_1)^2)$-expander subgraph with $\varepsilon_2 < 1/1000$, $d(G_1) \geq d(G'[U])/2 \geq d/200$, $\delta(G_1) \geq d(G_1)/2$ and $\Delta(G_1) \leq \Delta(G'[U]) \leq c_0 d^2$. Let $n_1 := |V(G_1)|$.

If $d(G_1) \geq \exp\{(\log n_1)^{1/8}\}$, then we apply Lemma 2.4 to G_1. Then either we have a copy of TK_ℓ with $\ell = \Omega(d)$, in which case we are done, or we obtain a subgraph $G_2 \subseteq G_1$ with $d(G_2) \geq d(G_1)/2 \geq d/400$, $\delta(G_2) \geq d(G_2)/4$ and $\Delta(G_2) \leq d(G_2) \log^8 \frac{|V(G_2)|}{d(G_2)^2}$, which is an $(\varepsilon_1/8, 4\varepsilon_2 d(G_2)^2)$-expander. Since $|V(G_2)| \leq n_1$, we have that $d(G_2) \geq d(G_1)/2 \gg \log^{14} |V(G_2)|$. Applying Lemma 4.1 to G_2 gives a TK_ℓ with $\ell = \Omega(d(G_2)) = \Omega(d)$.

We may now assume that $d(G_1) \leq \exp\{(\log n_1)^{1/8}\}$. We want to apply Theorem 5.1 to G_1 to get a TK_ℓ with $\ell = \Omega(d(G_1)) = \Omega(d)$. Recall that $d(G_1)/2 \leq \delta(G_1) \leq \Delta(G_1) \leq c_0 d^2 \leq 72 d(G_1)^2$, where the last inequality follows from $d(G_1) \geq d/200$ and $c_0 \leq 1/1000$. It suffices to check that G_1 is an $(\varepsilon_1, d(G_1))$-expander.

Claim 5.5. *The graph G_1 is an $(\varepsilon_1, d(G_1))$-expander.*

Proof. Recall that G_1 is bipartite, C_4-free and $(\varepsilon_1, \varepsilon_2 d(G_1)^2)$-expander. For any set X of size $x \geq \varepsilon_2 d(G_1)^2/2$, $|\Gamma(X)| \geq x \cdot \varepsilon(x, \varepsilon_1, \varepsilon_2 d(G_1)^2) \geq x \cdot \varepsilon(x, \varepsilon_1, d(G_1))$, as $\varepsilon(x, \varepsilon_1, t)$ is an increasing function in t.

It is known that in C_4-free bipartite graphs of minimum degree k, any set of size at most $k^2/500$ expands by a rate of at least 2 (see e.g. Lemma 2.1 in [17]). Recall that $\delta(G_1) \geq d(G_1)/2$ and $\varepsilon_2 \leq 1/1000$, so $\varepsilon_2 d(G_1)^2/2 \leq 2\varepsilon_2 \delta(G_1)^2 \leq \frac{\delta(G_1)^2}{500}$. Since $\varepsilon(x, \varepsilon_1, d(G_1))$ is a decreasing function in x, for any $x \geq d(G_1)/2$, $\varepsilon(x, \varepsilon_1, d(G_1)) \leq \varepsilon(d(G_1)/2, \varepsilon_1, d(G_1)) = \frac{\varepsilon_1}{\log^2(7.5)} < 2$. Thus for any set X of size $d(G_1)/2 \leq x \leq \varepsilon_2 d(G_1)^2/2 \leq \frac{\delta(G_1)^2}{500}$, we have $|\Gamma(X)| \geq 2x \geq x \cdot \varepsilon(x, \varepsilon_1, d(G_1))$ as desired. $\square$

This gives the first alternative of the conclusion of Lemma 5.4.

Case 2: $|U'| \geq |U|/5 \geq \frac{4n/5}{5} \geq n/7$. Recall that $|W| \leq \frac{n}{c_0 d}$. Consider the subgraph $G_3 := G'[U', W]$, by deleting extra edges, we may assume that each vertex in U' has degree at most d in W. Then by the definition of U', we have

$$\frac{d}{11} \leq \frac{2|U'| \cdot d/20}{|U'| + |W|} \leq d(G_3) \leq \frac{2|U'| \cdot d}{|U'| + |W|} \leq 2d.$$

Set $p := C/d$. We will choose a random subset $W_0 \subseteq W$, in which each element of W is included with probability p independent of each other. We then choose some $U_0 \subseteq U'$ consisting of vertices of degree at most K in W_0. We will show that with positive probability, W_0 and U_0 have the desired properties. For simplicity, we define $G_4 := G_3[U', W_0]$.

We may assume that $|W| \geq \frac{n}{d^2}$, since otherwise $|U'| = \Omega(d^2|W|)$ and $\frac{e(G_3)}{|U'|} \geq \delta(U') \geq d/20 = \Omega(\Delta(U'))$. Then applying Lemma 5.2 to G_3 yields a TK_ℓ with $\ell = \Omega(d)$. Note that $\mathbb{E}|W_0| = p|W|$, by Chernoff's Inequality, w.h.p. $|W_0| \leq 2\mathbb{E}|W_0| = 2C|W|/d$. As mentioned above, we will delete vertices from U' with degree more than K in W_0 to form U_0. It suffices to show that w.h.p.

(i) $e(G_4) \geq 2C'|U'|$;

(ii) the number of vertices deleted (i.e., $U' \setminus U_0$) is at most $|U'|/10$ and the number of edges deleted (from G_4 to form $G_3[U_0, W_0] = G'[U_0, W_0]$) is at most $C'|U'|$.

It then follows that $|U_0| \geq 9|U'|/10 \geq |U|/6$ and the number of edges in $G_0 = G'[U_0, W_0]$ is at least $e(G_4) - C'|U'| \geq C'|U'| \geq C'|U_0|$ as desired.

For (i), recall that by Lemma 5.3, $\Delta(G_3) \leq d^3$. For each vertex $v_i \in W$, define a random variable X_i taking value $\deg_{G_3}(v_i)$ if $v_i \in W_0$ and 0 otherwise. Then $e(G_4) = \sum_{i \leq |W|} X_i$ and

$$\mathbb{E}(e(G_4)) = \sum_{i \leq |W|} \mathbb{E}X_i = \sum_{v_i \in W} p \cdot \deg_{G_3}(v_i) = p \cdot e(G_3) \geq \frac{C}{d} \cdot \frac{d}{20} \cdot |U'| \geq 4C'|U'|.$$

Recall that $\frac{n}{d^2} \leq |W| \leq \frac{n}{c_0 d}$ and $d \leq \log^{14} n$. Applying Theorem 2.6 with $f(\mathbf{X}) = \sum X_i$, $\sigma_i = d^3$ and $t = \mathbb{E}(e(G_4))/2 \geq 2C'|U'| \geq \frac{2C'n}{7} \geq \frac{2C'}{7} \cdot c_0 d|W| \geq c_0 d|W|$, we have that

$$\mathbb{P}\left[e(G_4) \leq \frac{1}{2}\mathbb{E}(e(G_4))\right] \leq 2e^{-\frac{2(c_0 d|W|)^2}{d^6|W|}} = e^{-c_0^2|W|/d^4} \leq e^{-c_0^2 n/d^6} \to 0.$$

For (ii), for each $u_i \in U'$, we define a random variable $Y_i := \deg_{G_4}(u_i)$. Note that for any two vertices $u_i, u_j \in U'$, if they have no common neighbor in W, then Y_i and Y_j are independent. Define an auxiliary dependency graph F on vertex set $\{Y_i\}_{i=1}^{|U'|}$, in which Y_i and Y_j are adjacent if and only if they are not independent. Since in G_3 every vertex in U' has degree at most d and every vertex in W has degree at most d^3, it follows that $\Delta(F) \le d^4$ and by Brook's theorem that $\chi(F) \le d^4 + 1$. Thus we can partition U' into $d^4 + 1$ classes, say $U' := Z_0 \cup Z_1 \cup \ldots \cup Z_{d^4}$, such that Y_i's corresponding to vertices in the same class are independent. First we discard classes of size smaller than n/d^6, the number of vertices we delete at this step is at most $\frac{n}{d^6} \cdot (d^4 + 1) \ll |U'|$. Thus we may assume that each class is of size at least n/d^6. Fix a class Z_j, for every $v \in Z_j$ and every $i \ge K \gg C$,

$$\mathbb{P}[\deg_{G_4}(v) = i] = \binom{\deg_{G_3}(v)}{i} p^i (1-p)^{\deg_{G_3}(v)-i} \le \frac{d^i}{i!} \cdot \frac{C^i}{d^i} \le e^{-i \log i/2} := q_i.$$

For each $1 \le i \le d$, let N_i ($N_{\ge i}$ resp.) be the number of vertices in Z_j of degree i (at least i resp.) in W_0. Then $\mathbb{E}N_i \le |Z_j| q_i$. For each $i \le \log^2 d$, by Chernoff's Inequality and recall that $d \le \log^{14} n$, we have

$$\mathbb{P}[N_i \ge 2\mathbb{E}N_i] < \exp\{-|Z_j| q_i/3\} \ll \exp\left\{-\frac{n}{d^6} \cdot e^{-\log^3 d}\right\} \ll \exp\left\{-\frac{n}{e^{(\log\log n)^4}}\right\}. \tag{2}$$

Note that for any $v \in Z_j$, $\mathbb{P}[\deg_{G_4}(v) \ge \log^2 d] \le \sum_{i=\log^2 d}^{d} q_i \ll e^{-\log^2 d}$. It follows that

$$\mathbb{P}[N_{\ge \log^2 d} \ge 2\mathbb{E}N_{\ge \log^2 d}] \ll \exp\left\{-|Z_j| \cdot e^{-\log^2 d}\right\} \ll \exp\left\{-\frac{n}{e^{(\log\log n)^3}}\right\}. \tag{3}$$

By (2), (3) and the union bound, the probability that there exists a class Z_j in which either $N_{\ge \log^2 d} \ge 2\mathbb{E}N_{\ge \log^2 d}$ or for some $i \le \log^2 d$, $N_i \ge 2\mathbb{E}N_i$ is at most

$$(d^4 + 1) \cdot \left(\log^2 d \cdot \mathbb{P}[N_i \ge 2\mathbb{E}N_i] + \mathbb{P}[N_{\ge \log^2 d} \ge 2\mathbb{E}N_{\ge \log^2 d}]\right) \to 0.$$

Note that $\sum_{K \le i \le \log^2 d} \mathbb{E}N_i \le \sum_{K \le i \le \log^2 d} q_i |Z_j| \ll e^{-K}|Z_j|$. Thus w.h.p. the number of vertices deleted is at most

$$\sum_j ((2 \sum_{K \le i \le \log^2 d} \mathbb{E}N_i + 2\mathbb{E}N_{\ge \log^2 d}) \cdot |Z_j|) \ll \sum_j (e^{-K} + e^{-\log^2 d}) \cdot |Z_j| < 2e^{-K}|U'| \ll |U'|.$$

The number of edges incident to vertices deleted in Z_j is at most

$$\sum_{K \le i \le \log^2 d} (2q_i |Z_j| \cdot i) + (\sum_{i=\log^2 d}^{d} 2q_i |Z_j|) \cdot d \ll (e^{-K} + d \cdot e^{-\log^2 d}) \cdot |Z_j| < 2e^{-K}|Z_j|.$$

Recall that every vertex in U' has degree at most d in W and that $|U'| \ge n/7$. Then summing over all classes, the total number of edges deleted is at most

$$\sum_{|Z_j| \ge n/d^6} 2e^{-K}|Z_j| + \sum_{|Z_k| \le n/d^6} d \cdot |Z_k| \le 2e^{-K}|U'| + (d^4 + 1) \cdot d \cdot \frac{n}{d^6} \ll |U'|.$$

□

6 Proof of Theorem 1.4

In this section, we will prove Theorem 1.4 using a variation of the Dependent Random Choice Lemma (see survey [5] for more details on the method of dependent random choice). The following lemma roughly says that in a dense C_4-free graph one can find a set in which every small subset has a large second common neighborhood.

Lemma 6.1. *Let $G = (A \cup B, E)$ be a C_4-free bipartite graph on n vertices with $cn^{3/2}$ edges and $|A| = |B| = \frac{n}{2}$, where $n > 1/c^{20}$. If there exist positive integers a, m, r and t such that*

$$c^{2t}n - \binom{n}{r}\left(\frac{m}{n/2}\right)^t \geq a, \tag{4}$$

then there exists $U \subseteq A$ with at least a vertices such that for every r-subset $S \subseteq U$, $|N_2(S)| \geq m$.

Proof. First notice that

$$\begin{aligned}\sum_{v\in A}|N_2(v)| &= \sum_{v\in B}(d(v)-1)d(v) = \sum_{v\in B}d(v)^2 - \sum_{v\in B}d(v) \geq \frac{n}{2}\left(\frac{\sum_{v\in B}d(v)}{n/2}\right)^2 - e(G)\\ &= \frac{n}{2}(2cn^{1/2})^2 - cn^{3/2} \geq c^2n^2.\end{aligned}$$

Pick a set $T \subseteq A$ of t vertices uniformly at random with repetition. Let $W := N_2(T) \subseteq A$ and put $X := |W|$. Then by the linearity of expectation and $t \geq 1$, we have

$$\begin{aligned}\mathbb{E}[X] &= \sum_{v\in A}\mathbb{P}(v \in N_2(T)) = \sum_{v\in A}\left(\frac{|N_2(v)|}{n/2}\right)^t = \left(\frac{2}{n}\right)^t \cdot \frac{n}{2} \cdot \left(\frac{1}{n/2}\sum_{v\in A}|N_2(v)|^t\right)\\ &\geq \left(\frac{n}{2}\right)^{1-t} \cdot \left(\frac{\sum_{v\in A}|N_2(v)|}{n/2}\right)^t \geq \left(\frac{n}{2}\right)^{1-t} \cdot (2c^2n)^t = 2^{2t-1}c^{2t}n \geq c^{2t}n.\end{aligned}$$

Let Y be the random variable counting the number of r-sets in W that have fewer than m common second neighbors. The probability for a fixed such r-set S to be in W is at most $\left(\frac{m}{n/2}\right)^t$. There are at most $\binom{n}{r}$ r-sets, hence

$$\mathbb{E}[X - Y] \geq c^{2t}n - \binom{n}{r}\left(\frac{m}{n/2}\right)^t \geq a.$$

Thus there exists a choice of T, such that $X - Y \geq a$. Delete one vertex from X for each such "bad" r-set from W, and the resulting set U has the desired property. $\square$

Claim 6.2. *When proving Theorem 1.4, we may assume that G is bipartite on $A \cup B$ with $|A| = |B| = n/2$, $d(G) = d$ and all vertices in B have degree smaller than $30d$.*

Proof. We may assume that for any $H \subseteq G$, $d(H) \leq d$, otherwise we can work in H instead. Let $X \subseteq V$ be the set of vertices of degree at least $10d$, thus $|X| \leq n/10$. Let $Y = V \setminus X$. Since $d(G[X]) \leq d$, we have $e(G[X]) \leq d|X|/2 \leq e(G)/10$. Take an $\frac{n}{2}$-subset B of Y uniformly at random and call $V \setminus B = A$. Then we have,

$$\mathbb{E}(e(G[A,B])) \geq 0.4[e(G[Y]) + e(G[X,Y])] = 0.4[e(G) - e(G[X])] \geq 0.36e(G).$$

Therefore there exists a choice of A, B such that $e(G[A,B]) \geq 0.36e(G)$. Hence we can replace G by $G' := G[A,B]$, and every vertex in B has degree less than $10d \leq 10 \cdot (d(G')/0.36) < 30d(G')$. $\square$

Proof of Theorem 1.4. Assume G satisfies the conditions of Claim 6.2 and apply Lemma 6.1 to G with the following parameters:

$$a = \frac{c^6 n^{1/2}}{240}, \quad r = 2, \quad t = \frac{\log n}{4\log(1/c)}, \quad m = \frac{c^6 n}{2}.$$

In order to prove that (4) is satisfied, we shall prove $2\binom{n}{2}\left(\frac{m}{n/2}\right)^t \leq c^{2t}n$ and $c^{2t}n \geq 2a$. Indeed,

$$2\binom{n}{2}\left(\frac{m}{n/2}\right)^t \leq c^{2t}n \quad \Leftarrow \quad n \leq \left(\frac{c^2 n/2}{m}\right)^t = \left(\frac{1}{c}\right)^{4t} \Leftarrow \log n \leq 4t \cdot \log\frac{1}{c} = \log n.$$

On the other hand, we have

$$c^{2t}n \geq 2a = \frac{c^6 n^{1/2}}{120} \Leftrightarrow \frac{120 n^{1/2}}{c^6} \geq \left(\frac{1}{c}\right)^{2t} \Leftarrow \log 120 + \frac{1}{2}\log n + 6\log\frac{1}{c} \geq 2t\log\frac{1}{c} = \frac{1}{2}\log n.$$

Thus there exists $U \subseteq A$ of size at least $a = \frac{c^6 n^{1/2}}{240}$ such that for every pair of vertices $S \subseteq U$, $|N_2(S)| \geq m = c^6 n/2$.

We embed a copy of TK_ℓ with $\ell = a = c^5 d/480$ greedily as follows: first embed all the core vertices arbitrarily to U. Then we connect all pairs of core vertices one by one, in an arbitrary order, with internally vertex-disjoint paths of length 4. Fix a pair of vertices $S \subseteq U$. For every vertex v in $N_2(S)$, call $C(v) := N(v) \cap \Gamma(S)$ its *connector set* and call v "bad" if $|C(v)| = 1$. Since G is C_4-free, $|N_1(S)| \leq 1$, so there are at most $\Delta(B) \leq 30d$ bad vertices in $N_2(S)$. Any vertex $v \in N_2(S)$ that is not bad has $|C(v)| = 2$. When connecting S, we will exclude from $N_2(S)$ the following vertices: (i) bad vertices (if they exist); (ii) vertices in U; (iii) vertices that were already used in previous connections; (iv) vertices whose connector set was used. It follows immediately that if there is a vertex left in $N_2(S)$, then together with its connector set, we can connect S.

For (i) and (ii), recall that there are at most $30d$ bad vertices and $|U| \leq \ell$. For (iii), there are at most $\binom{\ell}{2}$ such vertices, one for each pair of core vertices. Thus there are at least $m - 30d - \ell - \binom{\ell}{2} \geq c^6 n/2 - 60cn^{1/2} - \ell^2 \geq c^6 n/4$ many vertices left in $N_2(S)$.

For (iv), we say that two vertices in $N_2(S)$ have no *conflict* with each other if their connector sets are disjoint. Notice that every vertex v in $N_2(S)$ that is not bad can have a conflict with at most $|C(v)| \cdot \Delta(B) = 2\Delta(B) \leq 60d$ vertices. Thus we can find at least

$$\frac{c^6 n/4}{2\Delta(B)} \geq \frac{c^6 n}{240d} = \frac{c^6 n}{480cn^{1/2}} = \frac{c^5 n^{1/2}}{480} \geq 2\ell$$

not-previously-used vertices in $N_2(S)$ that are pairwise conflict-free. Again since G is C_4-free, any other core vertex in $U \setminus S$ can be adjacent to connector sets of at most 2 vertices in $N_2(S)$. Thus there are at least $2\ell - 2(\ell - 2) = 4$ vertices available in $N_2(S)$ to connect the pair of vertices in S. $\square$

7 Concluding Remarks

The proof of Theorem 1.3 is almost identical to the proof of Theorem 1.2. The only differences is to generalize Lemma 4.1 to $\{C_4, C_{2k}\}$-free graphs for any $k \geq 4$. First we need a result of Kühn and Osthus [10], which finds a C_4-free subgraph G' in a C_{2k}-free graph G for $k \geq 4$ such that $d(G') = \Omega(d(G))$. Then after cleaning $S_1(v_i)$ and $S_2(v_i)$(as in Section 4.2), $S_2(v_i)$ still has $\Omega(d^2)$ vertices. Recall that each vertex in $S_2(v_i)$ sends $\Omega(d)$ edges to $S_3(v_i)$, then by a well-known result of Bondy and Simonovits [2], we have that there are at least $\Omega(d^{3-3/(k+1)})$ vertices available in $S_3(v_i)$ after cleaning $S_1(v_i)$ and $S_2(v_i)$. We further clean $S_3(v_i)$ by deleting at most $\ell^2 \cdot diam$ vertices. For $k \geq 4$, $d^{3-3/(k+1)}\varepsilon(d^{3-3/(k+1)}) \gg \ell^2 \cdot diam + d^2$, thus the robust diameter property is guaranteed for all connections.

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