Explicit Ramsey graphs and orthonormal labelings

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Abstract

We describe an explicit construction of triangle-free graphs with no independent sets of size m and with $\Omega(m^{3/2})$ vertices, improving a sequence of previous constructions by various authors. As a byproduct we show that the maximum possible value of the Lovász θ-function of a graph on n vertices with no independent set of size 3 is $\Theta(n^{1/3})$, slightly improving a result of Kashin and Konyagin who showed that this maximum is at least $\Omega(n^{1/3}/\log n)$ and at most $O(n^{1/3})$. Our results imply that the maximum possible Euclidean norm of a sum of n unit vectors in R^n, so that among any three of them some two are orthogonal, is $\Theta(n^{2/3})$.

1 Introduction

Let $R(3,m)$ denote the maximum number of vertices of a triangle-free graph whose independence number is at most m. The problem of determining or estimating R(3,m) is a well studied Ramsey type problem. Ajtai, Komlós and Szemerédi proved in [1] that $R(3,m) \leq O(m^2/\log m)$, (see also [17] for an estimate with a better constant). Improving a result of Erdös , who showed in [7] that $R(3,m) \geq \Omega((m/\log m)^2)$, (see also [18], [13] or [4] for a simpler proof), Kim [10] proved, very recently, that the upper bound is tight, up to a constant factor, that is: $R(3,m) = \Theta(m^2/\log m)$. His proof, as well as that of Erdös, is probabilistic, and does not supply any explicit construction of such a graph. The problem of finding an explicit construction of triangle-free graphs of independence number m and many vertices has also received a considerable amount of attention. Erdös [8] gave an explicit construction of such graphs with

$$\Omega(m^{(2\log 2)/3(\log 3-\log 2)}) = \Omega(m^{1.13})$$

vertices. This has been improved by Cleve and Dagum [6], and improved further by Chung, Cleve and Dagum in [5], where the authors present a construction with

$$\Omega(m^{\log 6/\log 4}) = \Omega(m^{1.29})$$

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vertices. The best known explicit construction is given in [2], where the number of vertices is $\Omega(m^{4/3})$.

Here we improve this bound and describe an explicit construction of triangle free graphs with independence numbers m and $\Omega(m^{3/2})$ vertices. Our graphs are Cayley graphs and their construction is based on some of the properties of certain Dual BCH error-correcting codes. The bound on their independence numbers follows from an estimate of their Lovász θ-function. This fascinating function, introduced by Lovász in [14], can be defined as follows. If $G = (V, E)$ is a graph, an *orthonormal labeling* of G is a family $(b_v)_{v \in V}$ of unit vectors in an Euclidean space so that if u and v are distinct non-adjacent vertices, then $b_u^t b_v = 0$, that is, b_u and b_v are orthogonal. The θ-number $\theta(G)$ is the minimum, over all orthonormal labelings b_v of G and over all unit vectors c, of

$$max_{v \in V} \frac{1}{(c^t b_v)^2}.$$

It is known (and easy; see [14]) that the independence number of G does not exceed $\theta(G)$. The graphs G_n we construct here are triangle free graphs on n vertices satisfying $\theta(G_n) = \Theta(n^{2/3})$, and hence the independence number of G_n is at most $O(n^{2/3})$.

The construction and the properties of the θ-function settle a geometric problem posed by Lovász and partially solved by Kashin and Konyagin [12], [9]. Let Δ_n denote the maximum possible value of the Euclidean norm $|| \sum_{i=1}^n u_i ||$ of the sum of n unit vectors $u_1, \ldots, u_n$ in R^n, so that among any three of them some two are orthogonal. Motivated by the study of the θ-function, Lovász raised the problem of determining the order of magnitude of Δ_n. In [12] it is shown that $\Delta_n \leq O(n^{2/3})$ and in [9] it is proved that this is nearly tight, namely that $\Delta_n \geq \Omega(n^{2/3}/(\log n)^{1/2})$. Here we show that the upper bound is tight up to a constant factor, that is:

$$\Delta_n = \Theta(n^{2/3}).$$

The rest of this note is organized as follows. In Section 2 we construct our graphs and estimate their θ-numbers and their independence numbers. The resulting lower bound for Δ_n is described in Section 3. Our method in these sections combines the ideas of [9] with those in [2]. The final Section 4 contains some concluding remarks.

2 The graphs

For a positive integer k, let $F_k = GF(2^k)$ denote the finite field with 2^k elements. The elements of F_k are represented, as usual, by binary vectors of length k. If a, b and c are three such vectors, let (a, b, c) denote their concatenation, i.e., the binary vector of length $3k$ whose coordinates are those of a, followed by those of b and those of c. Suppose k is not divisible by 3 and put $n = 2^{3k}$. Let W_0 be the set of all nonzero elements $\alpha \in F_k$ so that the leftmost bit in the binary representation of α^7 is 0, and let W_1 be the set of all nonzero elements $\alpha \in F_k$ for which the leftmost bit of α^7 is

1. Since 3 does not divide k, 7 does not divide $2^k - 1$ and hence $|W_0| = 2^{k-1} - 1$ and $|W_1| = 2^{k-1}$, as when α ranges over all nonzero elements of F_k so does α^7.

Let G_n be the graph whose vertices are all $n = 2^{3k}$ binary vectors of length $3k$, where two vectors u and v are adjacent if and only if there exist $w_0 \in W_0$ and $w_1 \in W_1$ so that $u + v = (w_0, w_0^3, w_0^5) + (w_1, w_1^3, w_1^5)$, where here the powers are computed in the field F_k and the addition is addition modulo 2. Note that G_n is the Cayley graph of the additive group $(Z_2)^{3k}$ with respect to the generating set $S = U_0 + U_1 = \{u_0 + u_1 : u_0 \in U_0, u_1 \in U_1\}$, where $U_0 = \{(w_0, w_0^3, w_0^5) : w_0 \in W_0\}$, and U_1 is defined similarly. The following theorem summerizes some of the properties of the graphs G_n.

Theorem 2.1 *If k is not divisible by 3 and $n = 2^{3k}$ then G_n is a $d_n = 2^{k-1}(2^{k-1} - 1)$-regular graph on $n = 2^{3k}$ vertices with the following properties.*

1. *G_n is triangle-free.*

2. *Every eigenvalue μ of G_n, besides the largest, satisfies*

$$-9 \cdot 2^k - 3 \cdot 2^{k/2} - 1/4 \leq \mu \leq 4 \cdot 2^k + 2 \cdot 2^{k/2} + 1/4.$$

3. *The θ-function of G_n satisfies*

$$\theta(G_n) \leq n \frac{36 \cdot 2^k + 12 \cdot 2^{k/2} + 1}{2^k(2^k - 2) + 36 \cdot 2^k + 12 \cdot 2^{k/2} + 1} \leq (36 + o(1)) n^{2/3},$$

where here the $o(1)$ term tends to 0 as n tends to infinity.

Proof. The graph G_n is the Cayley graph of Z_2^{3k} with respect to the generating set $S = S_n = U_0 + U_1$, where U_i are defined as above.

Let A_0 be the $3k$ by $2^{k-1} - 1$ binary matrix whose columns are all vectors of U_0, and let A_1 be the $3k$ by 2^{k-1} matrix whose columns are all vectors of U_1. Let $A = [A_0, A_1]$ be the $3k$ by $2^k - 1$ matrix whose columns are all those of A_0 and those of A_1. This matrix is the parity check matrix of a binary BCH-code of designed distance 7 (see, e.g., [16], Chapter 9), and hence every set of six columns of A is linearly independent over $GF(2)$. In particular, all the sums $(u_0 + u_1)_{u_0 \in U_0, u_1 \in U_1}$ are distinct and hence $|S_n| = |U_0||U_1|$. It follows that G_n has 2^{3k} vertices and it is $|S_n| = 2^{k-1}(2^{k-1} - 1)$ regular.

The fact that G_n is triangle-free is equivalent to the fact that the sum (modulo 2) of any set of 3 elements of S_n is not the zero-vector. Let $u_0 + u_1$, $u_0' + u_1'$ and $u"_0 + u"_1$ be three distinct elements of S_n, where $u_0, u_0', u"_0 \in U_0$ and $u_1, u_1', u"_1 \in U_1$. If the sum (modulo 2) of these six vectors is zero then, since every six columns of A are linearly independent, every vector must appear an even number of times in the sequence $(u_0, u_0', u"_0, u_1, u_1', u"_1)$. However, since U_0 and U_1 are disjoint this implies that every vector must appear an even number of times in the sequence $(u_0, u_0', u"_0)$ and this is clearly impossible. This proves part 1 of the theorem.

In order to prove part 2 we argue as follows. Recall that the eigenvalues of Cayley graphs of abelian groups can be computed easily in terms of the characters of the group. This result, decsribed in, e.g., [15], implies that the eigenvalues of the graph G_n are all the numbers

$$\sum_{s \in S_n} \chi(s),$$

where χ is a character of Z_2^{3k}. By the definition of S_n, these eigenvalues are precisely all the numbers

$$(\sum_{u_0 \in U_0} \chi(u_0))(\sum_{u_1 \in U_1} \chi(u_1)).$$

It follows that these eigenvalues can be expressed in terms of the Hamming weights of the linear combinations (over $GF(2)$) of the rows of the matrices A_0 and A_1 as follows. Each linear combination of the rows of A of Hamming weight $x+y$, where the Hamming weight of its projection on the columns of A_0 is x and the weight of its projection on the columns of A_1 is y, corresponds to the eigenvalue

$$(2^{k-1} - 1 - 2x)(2^{k-1} - 2y).$$

Our objective is thus to bound these quantities.

The linear combinations of the rows of A are simply all words of the code whose generating matrix is A, which is the dual of the BCH-code whose parity-check matrix is A. It is known (see [16], pages 280-281) that the Carlitz-Uchiyama bound implies that the Hamming weight $x+y$ of each non-zero codeword of this dual code satisfies

$$2^{k-1} - 2^{1+k/2} \leq x + y \leq 2^{k-1} + 2^{1+k/2}. \tag{1}$$

Let p denote the characteristic vector of W_1, that is, the binary vector indexed by the non-zero elements of F_k which has a 1 in each coordinate indexed by a member of W_1 and a 0 in each coordinate indexed by a member of W_0. Note that the sum (modulo 2) of p and any linear combination of the rows of A is a non-zero codeword in the dual of the BCH-code with designed distance 9. Therefore, by the Carlitz-Uchiyama bound, the Hamming weight of the sum of p with the linear combination considered above, which is $x + (2^{k-1} - y)$, satisfies

$$2^{k-1} - 3 \cdot 2^{k/2} \leq x + 2^{k-1} - y \leq 2^{k-1} + 3 \cdot 2^{k/2}. \tag{2}$$

Since for any two reals a and b,

$$-(\frac{a-b}{2})^2 \leq ab \leq (\frac{a+b}{2})^2$$

we conclude from (1) that

$$(2^{k-1} - 1 - 2x)(2^{k-1} - 2y) \leq \frac{(2^k - 1 - 2(x+y))^2}{4} \leq 4 \cdot 2^k + 2 \cdot 2^{k/2} + 1/4.$$

Similarly, (2) implies that

$$(2^{k-1}-1-2x)(2^{k-1}-2y) \geq -\frac{(1+2(x-y))^2}{4} \geq -9\cdot 2^k - 3\cdot 2^{k/2} - 1/4.$$

This completes the proof of part 2 of the theorem.

Part 3 follows from part 2 together with Theorem 9 of [14] which asserts that for d-regular graphs G with eigenvalues $d=\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_n$,

$$\theta(G) \leq \frac{-n\lambda_n}{\lambda_1-\lambda_n}.$$

It is worth noting that the fact that the right hand side in the last inequality bounds the independence number of G is due to A. J. Hoffman. □

Since the independence number of each graph G does not exceed $\theta(G)$ the following result follows.

Corollary 2.2 *If k is not divisible by 3 and $n=2^{3k}$, then the graph G_n is a triangle-free graph with independence number at most $(36+o(1))n^{2/3}$.* □

Let G_n be one of the graphs above and let $\overline{G}_n$ denote its complement. Since G_n is a Cayley graph, Theorem 8 in [14] implies that $\theta(\overline{G}_n)\theta(G_n)=n$ and hence, by Theorem 2.1, $\theta(\overline{G}_n) \geq (1+o(1))\frac{1}{36}n^{1/3}$.

In [9] it is proved (in a somewhat disguised form), that for any graph H with n vertices and no independent set of size 3, $\theta(H) \leq 2^{2/3}n^{1/3}$. (See also [3] for an extension). Since $\overline{G}_n$ has no independent set of size 3 and since for every graph H, $\theta(H)\theta(\overline{H}) \geq n$ (see Corollary 2 of [14]) the following result follows.

Corollary 2.3 *If k is not divisible by 3 and $n=2^{3k}$, then $\theta(G_n)=\Theta(n^{2/3})$ and $\theta(\overline{G}_n)=\Theta(n^{1/3})$. Therefore, the minimum possible value of the θ-number of a triangle-free graph on n vertices is $\Theta(n^{2/3})$ and the maximum possible value of the θ-number of an n-vertex graph with no independent set of size 3 is $\Theta(n^{1/3})$.*

3 Nearly orthogonal systems of vectors

A system of n unit vectors $u_1,\ldots,u_n$ in R^n is called *nearly orthogonal* if any set of three vectors of the system contains an orthogonal pair. Let Δ_n denote the maximum possible value of the Euclidean norm $||\sum_{i=1}^n u_i||$, where the maximum is taken over all systems $u_1,\ldots,u_n$ of nearly orthogonal vectors. Lovász raised the problem of determining the order of magnitude of Δ_n. Konyagin showed in [12] that $\Delta_n \leq O(n^{2/3})$ and that

$$\Delta_n \geq \Omega(n^{4/3-\log 3/2\log 2}) \geq \Omega(n^{0.54}).$$

The lower bound was improved by Kashin and Konyagin in [9], where it is shown that

$$\Delta_n \geq \Omega(n^{2/3}/(\log n)^{1/2})$$

.

The following theorem asserts that the upper bound is tight up to a constant factor.

Theorem 3.1 *There exists an absolute positive constant a so that for every n*

$$\Delta_n \geq an^{2/3}.$$

Thus, $\Delta_n = \Theta(n^{2/3})$.

Proof. It clearly suffices to prove the lower bound for values of n of the form $n = 2^{3k}$, where k is an integer and 3 does not divide k. Fix such an n, let $G = G_n = (V, E)$ be the graph constructed in the previous section and define $\theta = \theta(G)$. By Theorem 2.1, $\theta \leq (36 + o(1))n^{2/3}$. By the definition of θ there exists an orthonormal labeling $(b_v)_{v \in V}$ of G and a unit vector c so that $(c^t b_v)^2 \geq 1/\theta$ for every $v \in V$. Therefore, the norm of the projection of each b_v on c is at least $1/\sqrt{\theta}$ and by assigning appropriate signs to the vectors b_v we can ensure that all these projections are in the same direction. With this choice of signs, the norm of the projection of $\sum_{v \in V} b_v$ on c is at least $n/\sqrt{\theta}$, implying that

$$|| \sum_{v \in V} b_v || \geq n/\sqrt{\theta} \geq (\frac{1}{6} - o(1))n^{2/3}.$$

Note that since the vectors b_v form an orthonormal labeling of G, which is triangle-free, among any three of them there are some two which are orthogonal. This implies that $(b_v)_{v \in V}$ is a nearly orthogonal system and shows that for every $n = 2^{3k}$ as above

$$\Delta_n \geq (\frac{1}{6} - o(1))n^{2/3},$$

completing the proof of the theorem. □

4 Concluding remarks

The method applied here for explicut constructions of triangle-free graphs with small independence numbers cannot yield asymptotically better constructions. This is because the independence number is bounded here by bounding the θ-number which, by Corollary 2.3, cannot be smaller than $\Theta(n^{2/3})$ for any triangle-free graph on n vertices.

Some of the results of [9] can be extended. In a forthcoming paper with N. Kahale [3] we show that for every $k \geq 3$ and every graph H on n vertices with no independent set of size k,

$$\theta(H) \leq Mn^{1-2/k}, \tag{3}$$

for some absolute positive constant M. It is not known if this is tight for $k > 3$. Combining this with some of the properties of the θ-function, this can be used to show that for every $k \geq 3$ and any system of n unit vectors $u_1, \ldots, u_n$ in R^n so that among any k of them some two are orthogonal, the inequality

$$||\sum_{i=1}^{n} u_i|| \leq O(n^{1-1/k})$$

holds. This is also not known to be tight for $k > 3$. Lovász (cf. [11]) conjectured that there exists an absolute constant c so that for every graph H on n vertices and no independent set of size k,

$$\theta(H) \leq ck\sqrt{n}.$$

Note that this conjecture, if true, would imply that the estimate (3) above is *not* tight for all fixed $k > 4$.

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