Estimates of the Distance Distribution of Codes and Designs *

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Abstract

We consider the problem of bounding the distance distribution for unrestricted block codes with known distance and/or dual distance. Applying the polynomial method, we provide a general framework for previously known results. We derive several upper and lower bounds both for finite length and for sequences of codes of growing length. Asymptotic results in the paper improve previously known estimates. In particular, we prove the best known bounds on the binomiality range of the distance spectrum of codes with a known dual distance.

Index Terms — Binomial spectrum, constant weight codes, distance distribution, Krawtchouk polynomials, polynomial method.

1 Introduction

Intuitively it is clear that if the distance of a code is known, its distance distribution cannot be arbitrary. This paper is an attempt to quantify this statement. The distance distribution of a code with given parameters is important, in particular, for bounding the probability of decoding error under different decoding procedures from maximum likelihood decoding to error detection. Apart from this, it can be helpful in revealing structural properties of codes and establish nonexistence of some codes.

Our main tool is the polynomial (linear programming) method. This approach was pioneered by Sidel'nikov [25] and applied to BCH codes correcting a small number of errors. Essentially the only feature of BCH codes used in [25] was the width of the dual weight spectrum, known due to the Carlitz-Uchiyama bound. This study was taken up in [8], [13], [14], [15], [11]. These papers focused on establishing the range of weights in which the distance distribution of a code C is close to the average distribution of a code chosen in the Hamming space H_2^n with uniform probability (i.e., the binomial spectrum $A_w = \binom{n}{w}|C|/2^n$). However, implicitly some of these works contained bounds on the distance distribution of any code with known distance d or dual distance d'.

Another approach to bounding distance spectrum of (linear) codes with a known distance and/or dual distance was proposed in [9], see also [10]. In the frame of the polynomial method

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these results can be viewed as equivalents of the Singleton bound (see more on this in [1], [3]). Generally the method in [9], [10] seems to be somewhat weaker than the polynomial method employed here.

In Sect. 2 of this paper we formulate a general bound on the distance distribution of a code in a Q-polynomial association scheme. The most detailed analysis is performed for H_2^n. By modifying some polynomials known in Delsarte's theory we derive bounds on the distance distribution of a code with given d and d'. We also specify the results for the cases when only d is known (i.e., d' can be any number between 0 and n), and vice versa, only d' is known. The results can be summarized as follows. For a given code with known d or d' the gap between the lower and upper bounds derived below depends on the "quality" of the code: the better the code, the smaller the gap. For some optimal codes the bounds turn out to be tight. Asymptotic versions of the bounds improve previously known results; in particular, we prove that the distance distribution of a design of a given strength in H_2^n is bounded above by the binomial distribution for a wider range of distances than previously known. From a purely coding-theoretic point of view the most important problem studied in the paper is bounding the distance distribution of a code with a known distance d. A nontrivial estimate of it for large values of the distance is given in Theorem 3. This estimate in a large range of parameters is better than bounds on the size of a code of constant weight and distance d.

Our results imply the following facts, made more precise in Section 3:

– if a family of codes meets the upper bound from [23] then every small segment of distance values contains a binomial component in the distance distribution [1];

– if the distance distribution of any family of codes is bounded above by the binomial spectrum, then every small segment of distance values, except maybe distances close to the minimum distance of the code, contains a binomial component.

Sections 3, 5 deal with different ranges of code parameters. In each of these sections we first derive a general bound on the distance distribution for some fixed d and d' and then look at particular cases when only one of these two parameters is known. Accordingly, the corresponding subsections have titles *Codes* and *Designs*. In Section 4 we use the general method of Sect. 2 to derive an asymptotic bound on the distance distribution of constant weight codes. In Appendix A we provide an alternative proof of Theorem 3. It is based on new inequalities for orthogonal polynomials found recently in [12], which may be useful also in other coding problems.

Asymptotic results claimed in the paper are related to sequences of codes of growing length n. For instance, when we say that a code meets a certain asymptotic upper (lower) bound relating R and δ, we actually mean that there exists a sequence of codes whose rate tends to R as n grows and the distance d/n is in the limit not greater (less) than δ. Asymptotic bounds on other parameters are treated in a similar fashion.

Let $H(x) = -x\log x - (1-x)\log(1-x)$ be the binary entropy function. (The base of logarithms is 2 throughout.) In the paper A_i is always the element of the distance distribution of a code of length n and a_ξ is its exponent: $a_\xi = \frac{1}{n}\log A_{\xi n}$.

[1] It is not known presently whether such codes exist. We concur with a conjecture in [23] that they do not.

2 Preliminaries

Let X be a finite metric space with distance function $\partial(\cdot,\cdot)$ and let $C \subset X$ be a code. Let D be the diameter of X. The distance distribution of the code is a $(D+1)$-vector $(A_0, A_1, \ldots, A_D)$, where $A_i = (1/|C|)|\{(\mathbf{c},\mathbf{c}') \in C^2 : \partial(\mathbf{c},\mathbf{c}') = i\}|$. Suppose X affords the structure of a Q-polynomial association scheme and let $q_t(x)$, $t = 0, 1, \ldots, D$, denote the corresponding set of Q-polynomials. The Q-transform of the distance distribution of C is defined as a vector $(A'_0, A'_1, \ldots, A'_D)$, where

$$A'_j = \frac{1}{|C|}\sum_{i=0}^{D} A_i q_j(i), \tag{1}$$

$$\sum_{j=0}^{D} A'_j = |X|/|C|,$$

and by the Delsarte inequalities [6] all the numbers $A_i{}'$ are nonnegative. We have $A_0 = A'_0 = 1$; if $d = d(C)$ is the minimum distance of C, then $A_1 = \cdots = A_{d-1} = 0$. Furthermore, if $d' - 1$ is the strength of C as a design in X, then $A_1, \ldots, A_{d'-1} = 0$. Below we call d' the dual distance. We write $A_i(C)$ when we need to specify the code.

Let $g_w(x)$ be a real function defined on $\{0, 1, \ldots, D\}$, where $w, 0 \le w \le D$, is an integer parameter. Define a moment function of the distance distribution of C,

$$F_w(C) := \sum_{i=d}^{D} g_w(i) A_i(C).$$

We propose to derive bounds on $F_w(C)$. The reason for introducing the parameter w is to make expressions for the moment function algebraically independent for different w; see more on this in the end of this section.

Below we derive bounds on F_w for any code with a given d and/or d'. In this case we write $F_w(d, d')$. The same meaning is ascribed to the distance coefficients $A_i(d, d')$ and their exponents $a_\xi(\delta, \delta')$ (we put $i = \xi n, d = \delta n, d' = \delta' n$).

The following theorem enables us to construct upper and lower bounds on $F_w(d, d')$.

Theorem 1 *Let $Z_w(x) = \sum_{i=0}^{D} z_i q_i(x)$ be a polynomial such that*

$$z_i \le 0 \text{ for } d' \le i \le D, \text{ and } Z_w(i) \ge g_w(i) \text{ for } d \le i \le D. \tag{2}$$

Then

$$F_w(d, d') \le |C| z_0 - Z_w(0). \tag{3}$$

Let $Y_w(x) = \sum_{i=0}^{D} y_i q_i(x)$ be a polynomial such that

$$y_i \ge 0 \text{ for } d' \le i \le D, \text{ and } Y_w(i) \le g_w(i) \text{ for } d \le i \le D. \tag{4}$$

Then

$$F_w(d, d') \ge |C| y_0 - Y_w(0). \tag{5}$$

PROOF. Using (1), we obtain

$$\sum_{i=0}^{D} Z_w(i)A_i = \sum_{i=0}^{D} A_i \sum_{j=0}^{D} z_j q_j(i) = \sum_{j=0}^{D} z_j |C| A_j{}' \le z_0|C|$$

Hence

$$F_w(d,d') = \sum_{i=d}^{D} g_w(i)A_i \le \sum_{i=d}^{D} Z_w(i)A_i \le z_0|C| - Z_w(0).$$

The proof of inequality (5) is similar. □

Remark *Bounds on $F_w(d,d')$ also imply bounds on $A_j(d,d')$ for any fixed j. Indeed, let $g_w(i) \ge 0, i = d, \ldots, n$, and $g_w(j) > 0$. Then*

$$A_j(d,d') \le \frac{F_w(d,d')}{g_w(j)}. \tag{6}$$

Regarding lower bounds, it is convenient to choose $g_w(i) > 0$ for $i = d, d+1, \ldots, a$ and $g_w(i) \le 0$ for $i = a+1, \ldots, D$, where a is some number that usually depends on w. Then if we are able to establish that $F_w(d,d') > 0$, this implies the existence of $j \in [d,a]$ such that

$$A_j(d,d') \ge \frac{F_w(d,d')}{g_w(j)}. \tag{7}$$

While such estimates can be asymptotically tight, they are too crude for codes of finite length. We discuss two ways of sharpening them. Denote by $\underline{F}_w(d,d')$ and $\overline{F}_w(d,d')$ lower and upper bounds on $F_w(d,d')$ and by $\underline{A}_j$ and by $\overline{A}_j$ lower and upper bounds on $A_j(d,d')$, respectively.

In [11] the following procedure was suggested to estimate the distance distribution of BCH codes. (The procedure actually works for any code with known d and d'.) First estimate A_d as follows:

$$\frac{\underline{F}_w(d,d')}{g_w(d)} \le A_d(d,d') \le \frac{\overline{F}_w(d,d')}{g_w(d)}.$$

Next, estimate other spectrum components through the recursion

$$\frac{1}{g_w(j)}\left(\underline{F}_w(d,d') - \sum_{i=d}^{j-1} g_w(i)\overline{A}_i\right) \le A_j(d,d') \le \frac{1}{g_w(j)}\left(\overline{F}_w(d,d') - \sum_{i=d}^{j-1} g_w(i)\underline{A}_i\right). \tag{8}$$

In the present paper we use a different approach, which proved to be better in our examples. Namely, we choose the function g so that the matrix

$$G = [g_{wi}] = g_w(i), d \le w, i \le n, \tag{9}$$

is nonsingular. Then we compute

$$U = G^{-1} = [u_{ji}], d \le j, i \le n,$$

and find lower and upper bounds on $A_j(d,d')$ as follows:

$$\sum_{i=d}^{n} u_{ji} b_i \le A_j(d,d') \le \sum_{i=d}^{n} u_{ji} c_i, \tag{10}$$

where

$$b_i = \begin{cases} \overline{F}_i(d,d'), & \text{if } u_{ji} \le 0, \\ \underline{F}_i(d,d'), & \text{if } u_{ji} \ge 0; \end{cases} \quad \text{and } c_i = \begin{cases} \overline{F}_i(d,d'), & \text{if } u_{ji} \ge 0, \\ \underline{F}_i(d,d'), & \text{if } u_{ji} \le 0. \end{cases}$$

Our main examples are $X = H^n$, the Hamming scheme, and $X = J^{w,n}$, the binary Johnson scheme. If $X = H^n$ then $q_t(x) = K_t(x)$, where

$$K_t(x) = \sum_{i=0}^{n} (-1)^i \binom{x}{i} \binom{n-x}{t-i} (q-1)^{t-i}, \tag{11}$$

is a Krawtchouk polynomial. Note that if C is a linear code in H^n, then d' is the distance of the orthogonal code C'.

A polynomial that satisfies (2) or (4) will be called feasible. In what follows we construct several feasible polynomials and use them to derive bounds on the distance distribution, relying on (6) and (7) for growing code length and on (10) for codes of finite length.

3 An asymptotic bound

In this section we will construct polynomials $Z_w(x)$ and $Y_w(x)$ with the help of the Christoffel-Darboux kernel (43).

Denote by $x_1^{(t)}$ the smallest root of $K_t(x)$. Let $t = \frac{n}{2} - \sqrt{d(n-d)}, \tau = \frac{t}{n}$, and $\delta = \frac{d}{n}$. Let us choose $g_w(i)$ and $Z_w(i)$ as follows:

$$g_w(i) = (K_w(i))^2$$

and

$$Z_w(i) = (K_w(i))^2 - \frac{c}{a-i}(K_{t+1}(i) + K_t(i))^2, \tag{12}$$

where a is such that

$$x_1^{(t+1)} \le a \le x_1^{(t)} \text{ and } \frac{K_t(a)}{K_{t+1}(a)} = -1.$$

We assume through the rest of this section that d' is even.

Proposition 2 *Let C be a code with distance d and dual distance d'. Let*

$$c = \begin{cases} \frac{t+1}{2} \frac{\binom{n-d'}{w-d'/2}}{\binom{n-d'}{t-d'/2}}, & \text{if } d'/2 \le w \le t, \\ 0, & \text{if } 0 \le w \le d'/2. \end{cases} \tag{13}$$

Then for sufficiently large n

$$F_w(d,d') \le |C| \left[\binom{n}{w} - c\binom{n}{t} \right] - \binom{n}{w}^2 + \frac{c}{a} \left[\binom{n}{t+1} + \binom{n}{t} \right]^2, \ 0 \le w < t \le \frac{n}{2}. \tag{14}$$

PROOF. By (46), $\frac{1}{n}x_1^{(t)} = \frac{1}{2} - \sqrt{\tau(1-\tau)} + o(1) = \delta + o(1)$. Therefore for sufficiently large n

$$Z_w(i) \geq g_w(i), \ d \leq i \leq n.$$

The coefficients of the Krawtchouk expansion of the polynomial $\frac{1}{a-i}(K_{t+1}(i) + K_t(i))^2$, say β_j, can be estimated from below as follows [4]:

$$\beta_j \geq \frac{2}{t+1}\binom{n-j}{t-\frac{j}{2}}\binom{j}{\frac{j}{2}}. \tag{15}$$

By (44) in Appendix B, the Krawtchouk coefficients of $(K_w(i))^2$ are

$$\alpha_j = \binom{n-j}{w-\frac{j}{2}}\binom{j}{\frac{j}{2}}. \tag{16}$$

The definition of the constant c implies that $z_{d'} = \alpha_{d'} - c \cdot \beta_{d'} \leq 0$. Note that $z_{d'}$ tends to 0 for growing n. It is not difficult to check that β_j is decreasing on j slower than α_j when $0 \leq j \leq 2w$ (to verify this compare the quantities α_{j+1}/α_j and β_{j+1}/β_j). Hence

$$z_j \leq \alpha_j - c \cdot \beta_j \leq 0 \quad (j = d', \ldots, n).$$

Thus $Z_w(i)$ is feasible.

Now computing $Z_w(0)$ with the help of (45), we complete the proof. □

Let us consider the cases when only d or only d' is known.

3.1. Codes. We start with the case of known d, assuming that $d' = 0$ (note that if a polynomial is feasible for a given d and $d' = 0$ it is also feasible for any d'). Let

$$\omega^* = (1/2) - \sqrt{\xi(1-\xi)}. \tag{17}$$

Theorem 3 *Let C be a code of distance δn. Its distance distribution is bounded above as follows:*

$$a_\xi(\delta, 0) \leq H\Big(\frac{1}{2} - \sqrt{\delta(1-\delta)}\Big) + H(\xi) - 1 + o(1) \quad (\delta \leq \xi \leq 1/2). \tag{18}$$

PROOF. Let $\omega = w/n$. Substituting $d' = 0$ into (13), we get from (14)

$$a_\xi(\delta, 0) \leq H(\omega) + H(\tau) - \frac{1}{n}\log g_{\lfloor \omega n \rfloor}(\lfloor \xi n \rfloor) + o(1).$$

To estimate $A_{\lfloor \xi n \rfloor}$, we have to choose ω. A good choice is $\omega = \omega^*$ (in fact, this choice is optimal, though we leave this fact without proof). From (48) it follows that

$$\frac{1}{n}\log g_{\lfloor \omega^* n \rfloor}(\lfloor \xi n \rfloor) = 1 + H(\omega^*) - H(\xi).$$

Now a simple substitution completes the proof. □

Another proof of this theorem is given in Appendix A. It is based on some new bounds on orthogonal polynomials derived recently in [12].

Theorem 3 gives a universal bound on the growth of the distance coefficients in a code with a given distance. Let us examine the question when this bound is nontrivial. It can be trivial for one of the two reasons: the right-hand size of (18) is greater than the total size of the code, or it is greater than any known upper bound on the size of a code of constant weight ξn and distance δn.

Let us examine the last option. Let $R(\xi, \delta)$ be the maximal size of a code of constant weight ξn and Hamming distance δn. One of the bounds on this quantity is [23]

$$R(\xi, \delta) \le R_1(\xi, \delta) := H\Big(\frac{1}{2}\Big(1 - \sqrt{1 - (\sqrt{4\xi(1-\xi) - \delta(2-\delta)} - \delta)^2}\Big)\Big) \qquad (19)$$
$$(0 \le \delta \le \xi(1-\xi));$$

for large distances this bound is the best known. A better bound for small δ was obtained in [24] based on a result in [18] (in this form it is given in [2]).

Proposition 4 [24] *Let*

$$\xi_0 = \arg\min_{(1-\sqrt{1-2\delta})/2 \le \alpha \le 1/2} 1 - H(\alpha) + R_1(\alpha, \delta).$$

Then

$$R(\xi, \delta) \le H(\xi) - H(\xi_0) + R_1(\xi_0, \delta) \qquad (\xi_0 \le \xi \le 1/2). \qquad (20)$$

Comparison with these results shows that we can estimate distance distributions better than the general bounds (19) and (20) for large code distances. More specifically, it is clear that whenever (20) is valid, is is better than (18) (indeed, the right-hand side of (20) equals $H(\xi) - 1$ plus the *second* bound of [23], as opposed to the first one in (18)). However, it is known that for $0.273 \le \delta \le 1/2$ the value $\xi_0 = 1/2$. For these δ bound (20) is void. Moreover, calculations show that in this range of distances, $R_1(\xi, \delta)$ in (19) as a bound on the distance distribution is also inferior to (18). For distances $0.24 \le \delta \le 0.273$ there is a segment of weights beginning with δ where (18) is better than both (20) and (19). The whole picture is shown in Fig. 1.

It is more difficult to compare (18) with the total size of the code since this bound does not involve explicitly the code rate R. As shown below, for putative sequences of codes meeting the 1st bound of [23], the bound (18) is tight, so it is certainly nontrivial for all $\delta \in (0, 1/2)$. For codes meeting the VG bound $R = 1 - H(\delta)$ the right-hand side of (18) is less than R whenever

$$(1 - H(\delta)) - (H((1/2) - \sqrt{\delta(1-\delta)}) + H(\xi) - 1) > 0. \qquad (21)$$

For small δ this holds true for all ξ outside a small segment around $1/2$ (for $\delta \to 0$ this segment shrinks to the point $1/2$).

Another approach to bounding the distance distribution of codes was taken in [20]. In particular, in [20] it is proved that in any *linear* code the number of vectors of any weight $i = \xi n$ does not exceed $O(|C|/\sqrt{n})$. When Theorem 3 is nontrivial (for instance, for all ξ such that (21) holds true), it shows that the number of vectors of weight i has a much slower

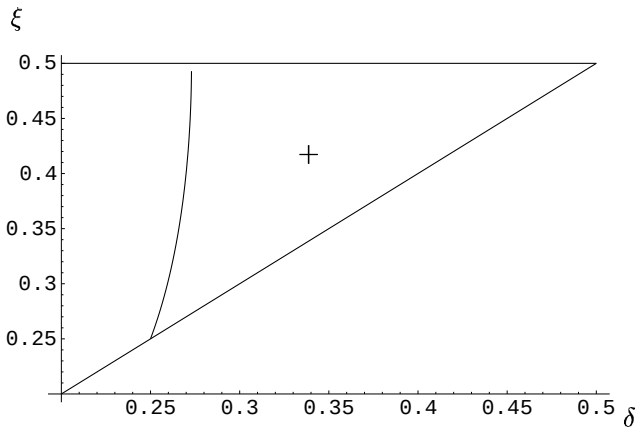


Figure 1: Region in the (δ, ξ)-plane, marked with a +, where (18) is the best estimate of the distance distribution

exponential growth than $|C|$. However, there is a range of code parameters when the bound in [20] is better than both. In [26] the authors study the threshold probability of a code C with a given distance d, i.e., the crossover probability $\theta(C)$ of a binary symmetric channel such that the error probability of maximum likelihood decoding of C in this channel equals $1/2$. They give a lower bound on $\theta(C)$ via an upper bound on the distance distribution of C and then rely on upper bounds on constant weight codes. Our estimate (18) sometimes yields a better bound on $\theta(C)$.

Theorem 3 together with earlier results implies interesting results on the distance distribution of certain sequences of codes. The following theorem is a combination of results in [22] and [15].

Theorem 5 *For sufficiently large n and any $0 \leq \omega \leq H^{-1}(R)$ there exists $\xi \in [\delta, \frac{1}{2} - \sqrt{\omega(1-\omega)}]$ such that*

$$a_\xi(\delta, 0) \geq R + H(\omega) - (2/n) \log K_{\lfloor \omega n \rfloor}(\lfloor \xi n \rfloor) + o(1). \tag{22}$$

Moreover, every subinterval of the interval $(\delta, 1/2)$ of length $n^{-\frac{1}{2}+\epsilon}, \epsilon > 0$, contains a point ξ such that this inequality holds true.

Now let us assume that the code G of rate R meets the first form of the linear programming bound from [23], i.e.

$$\delta(G) = \delta_{lp}(R) := 1/2 - \sqrt{H^{-1}(R)(1 - H^{-1}(R))}.$$

Then Theorems 3 and 5 imply the following necessary condition on the existence of G.

Corollary 1 *The distance distribution of G is asymptotically binomial in the following sense: the equality*

$$a_\xi(G) = R + H(\xi) - 1 + o(1)$$

holds for some ξ within every subinterval of length $n^{-\frac{1}{2}+\epsilon}, \epsilon > 0$, of the interval $(\delta_{lp}(R), 1/2)$.

PROOF. It follows from the observation that the right-hand sides of (18) and (22) under the assumptions of the corollary can be made the same. Indeed, let us put $\xi = \frac{1}{2} - \sqrt{\omega(1-\omega)}$ in Theorem 5. Then together with (48) we obtain $R + H(\xi) - 1 + o(1)$ on the right-hand side of (22). On the other hand, a substitution of $H\left(\frac{1}{2} - \sqrt{\delta(1-\delta)}\right) = R$ into (18) gives

$$a_\xi(G) \le R + H(\xi) - 1 + o(1), \quad \delta_{lp} < \xi < \frac{1}{2}$$

and the claim follows. □

This corollary complements a result in [2] in the following way. In that paper we proved that the distance distribution of codes meeting the second bound of [23] is asymptotically binomial for code rates $0.421 < R \le 1$. Here we prove the same for all $R \in (0,1)$ with respect to codes that meet the first bound of [23]. The first and second bounds coincide for $0 \le R \le 0.305$. Hence, as conclusion, binary codes of rate R that meet the McEliece et al. bounds (if such exist) are proved to have asymptotically binomial distance distribution for $R \in (0, 0.3) \cup (0.421, 1)$.

As another example, consider a sequence of codes with rate and distance related by $R = 1 - H(\delta)$ and with distance distribution $A_w \le n\binom{n}{w}|C|2^{-n}$ (these codes can be chosen among linear codes meeting the Varshamov-Gilbert bound). For them Theorem 5 implies the existence of an exactly binomial component in any subinterval of weights of length $n^{\frac{1}{2}+\epsilon}$ located between $n\delta_{lp}(R)$ and $n/2$. The proof is basically the same as that of Corollary 1; details are omitted.

3.2. Designs. The following bounds on the distance distribution of a code as a function of its dual distance were implicitly obtained in [14].

Theorem 6 [14]

$$a_\xi(0,\delta') \le \begin{cases} R + H(\xi) - 1 + o(1), & 0 \le \frac{1}{2} - \sqrt{\xi(1-\xi)} \le \delta'/2, \\ R + H(\delta'/2) - \frac{2}{n}\log K_{d'/2}(\lfloor \xi n \rfloor) + o(1), & \delta'/2 < \frac{1}{2} - \sqrt{\xi(1-\xi)} \le 1/2. \end{cases}$$

Actually the authors of [14] were interested in estimating the range of weights $\mathcal{I} \subset [0, 1/2]$ where the distance distribution of a code (design) is at most binomial: $a_\xi \le R + H(\xi) - 1 + o(1)$ for any $\xi \in \mathcal{I}$. Theorem 6 implies that $[1/2(1 - \sqrt{\delta'(2-\delta')}), 1/2] \subseteq \mathcal{I}$. We will now show that this inclusion generally is strict, thereby extending the binomiality interval, and also improve the second estimate in Theorem 6 for some code parameters.

Let us use the polynomial (12). To guarantee its feasibility for any d we put $d = 0$. If $\omega^* \le \delta'/2$ we choose $\omega = \omega^*$ (17). By (13) $c = 0$. Now with the help of (48) after simple computations we get the first case of Theorem 6. The more interesting case is the one with $\omega^* = \frac{1}{2} - \sqrt{\xi(1-\xi)} \ge \frac{\delta'}{2}$, i.e., $\xi \le (1/2)(1 - \sqrt{\delta'(2-\delta')})$. In this situation the choice of ω is a

priori unclear, and hence c can be greater than zero. Thus,

$$\begin{aligned} F_w(0,d') &\le |C|\Big[\binom{n}{w} - c\binom{n}{t}\Big] - \binom{n}{w}^2 + \frac{c}{a}\Big[\binom{n}{t+1} + \binom{n}{t}\Big]^2 \\ &\le |C|\binom{n}{w} + \frac{c}{a}\Big[\binom{n}{t+1} + \binom{n}{t}\Big]^2, \quad \frac{d'}{2} \le w \le n\Big[\frac{1}{2} - \sqrt{\xi(1-\xi)}\Big]. \end{aligned} \tag{23}$$

Let us compute the exponents of each term in (23):

$$\begin{aligned} \frac{1}{n}\log|C|\binom{n}{w} &= R + H(\omega) + o(1), \\ \frac{1}{n}\log\frac{c}{a}\Big[\binom{n}{t+1} + \binom{n}{t}\Big]^2 &= (1-\delta')H\Big(\frac{\omega - \delta'/2}{1-\delta'}\Big) + 2 - (1-\delta') + o(1) \\ &= (1-\delta')H\Big(\frac{\omega - \delta'/2}{1-\delta'}\Big) + 1 + \delta' + o(1). \end{aligned}$$

Eventually we obtain the theorem.

Theorem 7 *For any* $\omega \in [0, \frac{1}{2} - \sqrt{\xi(1-\xi)}]$

$$a_\xi(0,\delta') \lesssim -\frac{2}{n}\log K_{\lfloor \omega n \rfloor}(\lfloor \xi n \rfloor) + \max\{R + H(\omega), (1-\delta')H\Big(\frac{\omega - \delta'/2}{1-\delta'}\Big) + 1 + \delta'\}.$$

It follows from this theorem that for codes of sufficiently large size the interval of binomiality can be expanded compared to Theorem 6. Namely, let

$$\xi_1 := (1/2)(1 - \sqrt{\delta'(2-\delta')}),$$

and ξ_2 be the root of the equation $R = (1-\delta')H\big(\frac{\omega^* - \delta'/2}{1-\delta'}\big) + 1 + \delta' - H(\omega^*)$. If the root of this equation is negative, we put $\xi_2 = 0$.

Corollary 2 *Let C be a code of rate R with dual distance d'. For any $\xi \in [\min\{\xi_1, \xi_2\}, 1/2]$ the code C has asymptotically binomial distance distribution:*

$$a_\xi(0,\delta') \le R + H(\xi) - 1 + o(1).$$

This result can extend substantially the binomiality range in codes' spectra compared to Theorem 6; see the example in the end of Section 5.

4 Constant weight codes

In this section we apply Theorem 1 to codes in the Johnson space $J^{w,n}$. The corresponding metric $\partial(c,c')$ equals half the Hamming distance between c and c'. As above, let C be a code and $A = (A_0, A_1, \dots, A_w)$ be its distance distribution. In this case the family of q-polynomials is formed by some Hahn polynomials $Q_t(x)$, orthogonal on $(0,1,\dots,w)$ with weight $\mu(i) = \frac{\binom{w}{i}\binom{n-w}{i}}{\binom{n}{w}}$. Hahn polynomials share many properties of Krawtchouk polynomials. The collection

of basic facts was derived in [6], the asymptotics of the extremal zero was found in [23] (with a refinement in [19]), and the exponential asymptotics outside the oscillatory segment was computed in [1], [22].

The following theorem is proved similarly to Theorem 6 by taking in Theorem 1 $Z(x) = Q_t^2(x)$ with a suitable t dependent on ξ.

Theorem 8 *Let C be a code of rate R in $J^{w,n}$ with dual distance $d' = \delta' n$. Let $n \to \infty$ and $w = \omega n$. Then*

$$a_\xi(0,\delta') \lesssim \begin{cases} R + \omega H\left(\frac{\xi}{\omega}\right) + (1-\omega) H\left(\frac{\xi}{1-\omega}\right) - H(\omega) & \text{if } x_1^{(d'/2)}/n < \xi \le 2\omega(1-\omega); \\ R + H(\delta'/2) - (2/n)\log Q_{\frac{\delta'}{2}}(\xi n) & \text{if } \xi \le x_1^{(d'/2)}/n, \end{cases}$$

where

$$x_1^{(\tau n)} = n \frac{\omega(1-\omega) - \tau(1-\tau)}{1 + 2\sqrt{\tau(1-\tau)}}.$$

Note that the first of the two estimates, again, states that in a certain range depending on $d^\perp$, the distance distribution of a code is bounded above by the mathematical expectation of the distance distribution of a code chosen in $J^{w,n}$ with uniform probability. To justify this, notice that the sphere in $J^{w,n}$ of radius i has size $\binom{w}{i}\binom{n-w}{i}$, so the normalized uniform measure of the spheres in $J^{w,n}$ is given by $\mu(i)$. This theorem admits improvements along the lines of Theorem 7.

5 Bounds for high-rate codes

In this section we will construct several polynomials that give tight bounds on the distance distributions of good codes of rate close to 1.

We start with deriving bounds for codes of finite length, confining ourselves to the case of odd minimum distance $d = 2e+1$. The case of even d can be analyzed similarly. Upon deriving upper and lower bounds on the distance distribution of a code with known d, d', we consider a few examples in which the bounds are virtually tight. In one example we also compute bounds on the probability of undetected error and of decoding error, illustrating the use of the distance distribution coefficients. Then we turn to asymptotics, again looking separately at codes and designs. The bounds derived in this part supplement the results of the previous section, covering the range of code rates $R \to 1$.

Let n be fixed. For any w, $d \le w \le n$, let $g_w(x) = \sum_j g_j K_j(x)$ be the polynomial of degree $\le n$ with the Krawtchouk coefficients

$$g_j = K_{w-e}(j) L_e(j) \quad (d \le w \le n),$$

where $L_e(x) = K_0(j) + K_1(j) + \ldots + K_e(j)$ is the Lloyd polynomial.

In what follows, we construct feasible polynomials $Z_w(i)$ and $Y_w(i)$, which enable us to compute numerically lower and upper bounds on the distance distribution of a code. Since these bounds cannot be formulated as closed-form expressions, we do not present the results in the form of theorems.

Let $Z_w(i)$ be the polynomial with the Krawtchouk coefficients

$$z_j = K_{w-e}(j)L_e(j) - cL_e^2(j). \tag{24}$$

Let us compute $g_w(i)$ and $Z_w(i)$. Using (41), (44), and (42) in Appendix B, we have

$$\begin{aligned}\sum_{j=0}^{n} K_{w-e}(j)K_t(j)K_j(i) &= \sum_{j=0}^{n} K_j(i)\sum_{s=0}^{n} p^s_{w-e,t}K_s(j)\\ &= 2^n p^i_{w-e,t}.\end{aligned}$$

From this we obtain

$$g_w(i) = 2^n \sum_{t=0}^{e} p^i_{w-e,t}. \tag{25}$$

In a similar way one can compute $Z_w(i)$. In particular, for $i \geq d$

$$\begin{aligned}\sum_j (L_e(j))^2 K_j(i) &= \frac{2^n}{\binom{n}{i}}\langle L_e^2, K_i\rangle = \frac{2^n}{\binom{n}{i}}\sum_{s,t}\langle K_sK_t, K_i\rangle\\ &= \frac{2^n}{\binom{n}{i}}\sum_{s,t}\sum_{u=0}^{s+t} p^u_{st}\langle K_u, K_i\rangle = 0.\end{aligned}$$

So we see that

$$Z_w(i) = g_w(i), \quad d \leq i \leq n, \tag{26}$$

$$Z_w(0) = -c\cdot 2^n \sum_{t=0}^{e}\binom{n}{t}. \tag{27}$$

This prompts the following choice of c:

$$c = \max_{d'\leq j\leq n} \frac{K_{w-e}(j)}{L_e(j)}. \tag{28}$$

It is clear that with this choice $z_j \leq 0$, $d' \leq j \leq n$; thus, $Z_w(i)$ is feasible. By (45) in Appendix B

$$z_0 = \binom{n}{w-e}\sum_{t=0}^{e}\binom{n}{t} - c\Big(\sum_{t=0}^{e}\binom{n}{t}\Big)^2. \tag{29}$$

Now one can compute numerically an upper estimate of $F_w(d,d')$ from Theorem 1 and (25)-(29).

To estimate $F_w(d,d')$ from below choose $Y_w(i)$ with the coefficients

$$y_j = K_{w-e}(j)L_e(j) - c(L_e(j))^2, \tag{30}$$

where

$$c = \max_{d'\leq j\leq n} -\frac{K_{w-e}(j)}{L_e(j)}.$$

This polynomial is feasible for the same reasons as the previous one.

Example 1 *For the sake of argument, let us apply the results of this section to perfect codes. Let C be a code with minimum distance $d = 2e + 1$ that meets the Hamming bound, that is*

$$|C| \sum_{t=0}^{e} \binom{n}{t} = 2^n. \tag{31}$$

Let us find an estimate for $A_d(C)$. Putting $w = d$ and simplifying, we obtain $g_d(d) = 2^n \binom{2e+1}{e+1}$. Now, using (26), (27), (29), and taking into account (31), we compute $\frac{1}{g_d(d)}(z_0|C| - z_{e+1}(0))$; so finally

$$A_d(C) \le \binom{n}{e+1} / \binom{2e+1}{e+1}.$$

Using the same arguments for the polynomial $Y_d(x)$, we get

$$A_d(C) \ge \binom{n}{e+1} / \binom{2e+1}{e+1}.$$

Thus we have derived the well-known expression for the minimum distance component of the distance distribution of a perfect code. Moreover, if C meets the Hamming bound, then from the definitions of the polynomials $g_w(i), Z_w(i)$, and $Y_w(i)$ and (31) we have

$$z_0|C| - Z_w(0) = y_0|C| - Y_w(0), \quad d \le w \le n.$$

In other words $F_w(C)$ is found exactly for all w. Now (8) or (10) enable us to reconstruct the entire distance distribution of C.

Example 2 *Let us estimate the distance distribution of a code C of length 47, size $9 \cdot 2^{38}$, and minimum distance 3, which is the best known for these parameters* [21]. *Computing the matrix (9), one can check that it is invertible. Now using in (10) the polynomials defined by (24) and (30), we find upper and lower bounds on the spectrum of the code. The results of computations for some values of j are presented in the following table (the bounds are computed for all $d \le j \le n$).*

j	3	4	5	6	7	8	14	18	22	24
$\log \overline{A}_j$	8.483	11.973	14.971	17.815	20.345	22.714	32.874	36.722	38.616	38.904
$\log \underline{A}_j$	7.938	11.675	14.312	17.468	19.643	22.333	32.306	35.881	37.146	36.650

One can see that the upper and lower bounds are close to one another. Using these bounds, let us find upper and lower bounds on the probability of undetected error $P_{ue}(C)$ and of decoding error $P_{de}(C)$ for C under complete decoding. We assume that codewords of C are sent over the binary symmetric channel with crossover probability p. Then

$$\sum_{i=d}^{n} \underline{A}_i p^i (1-p)^{n-i} \le P_{ue}(C) \le \sum_{i=d}^{n} \overline{A}_i p^i (1-p)^{n-i}$$

For P_{de}, let us assume that $c \in C$ is the vector transmitted over the channel and e is the error vector. We use the following crude estimates

$$\sum_{c' \ne c} \Pr(\partial(c', e) \le 1) \le P_{de}(C) \le 1 - \Pr(\|e\| \le 1).$$

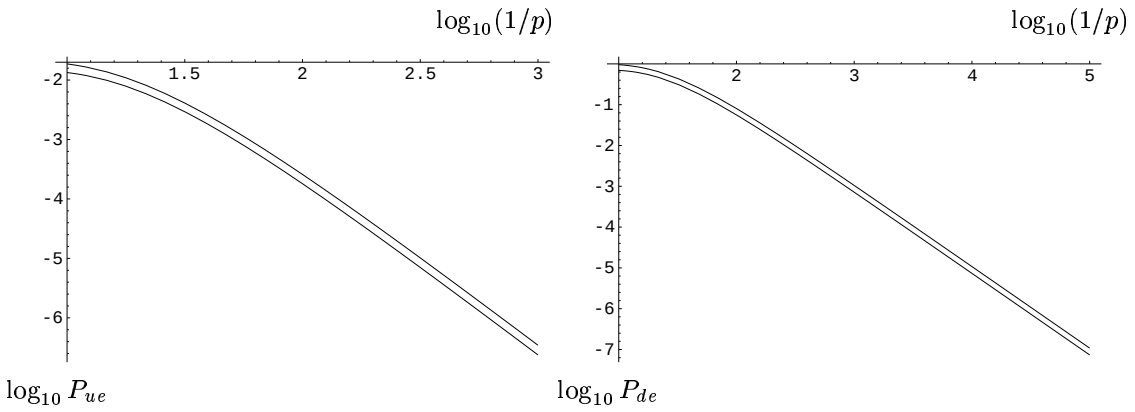


Figure 2: Estimates of P_{ue} and P_{de} for the $[47, 9 \cdot 2^{38}, 3]$ code of Example 3.

The results are shown in Fig. 2; in both cases the difference between the upper and lower bounds is within the 50% *range.*

If some additional information about a code or its dual code is available, we can tighten the bounds even further. Consider the following example.

Example 3 *Let C be an extended BCH code correcting $e = 3$ errors. C has length 2^m, dimension $2^m - 3m - 1$, and minimum distance 8. Since the code C' contains the all-one word, we can rewrite the estimates on $F_w(C)$ as follows:*

$$|C|(y_0 + y_n) - Y_w(0) \le F_w(C) \le |C|(z_0 + z_n) - Z_w(0),$$

where

$$z_j \le 0 \text{ and } y_j \ge 0 \text{ for } d' \le j \le n - d'.$$

It is well known that $d' \ge n/2 - 2\sqrt{n}$. Moreover, C' is a subcode of the Reed-Muller code of the second order, and therefore A'_j can be nonzero only if j is a multiple of $2^{\lceil m/2 \rceil - 1}$. Hence we have to guarantee nonpositivity of z_j and nonnegativity of y_j only for such j's. Define polynomials $g_w(i), Z_w(i)$, and $Y_w(i)$ for even w, $d \le w \le n - d$, by their coefficients as follows:

$$\begin{aligned} g_j &= K_{w-e}(j)K_e(j), \\ z_j &= K_{w-e}(j)K_e(j) - c_u \cdot (K_e(j))^2, \\ y_j &= K_{w-e}(j)K_e(j) + c_l \cdot (K_{e-1}(j))^2. \end{aligned}$$

Here c_u and c_l are the minimum possible nonnegative numbers such that z_j and y_j satisfy the aforementioned conditions. Since the second terms of $Z_w(i)$ and $Y_w(i)$ are positive, such c_l and c_u always exist.

This is all we need to compute bounds on $A_j(C)$ with the help of Theorem 1 and expression (10). For instance, let $m = 8$. The bounds for the first five distance distribution components are presented in the following table.

j	8	10	12	14	16
$\log \overline{A}_j$	24.860	33.969	42.790	51.135	59.060
$\log \underline{A}_j$	24.437	33.919	42.785	51.134	59.059

Note that these estimates are slightly better than the results in [11] and [8]. Estimates for the distance distribution of BCH codes with other values of e can be found similarly.

Now let us move to the asymptotic case. Let $V_w(i)$ be the polynomial with the coefficients

$$v_j = \frac{w+1}{2(a-j)}(K_{w+1}(j) + K_w(j))^2,$$

where a is a real number such that $x_1^{(w+1)} \le a \le x_1^{(w)}$ and $K_w(a) = -K_{w+1}(a)$. Let us define polynomials $g_w(i)$ and $Z_w(i)$ as follows:

$$\begin{aligned} g_w(i) &= 2^n \binom{n-i}{w-\frac{i}{2}} \binom{i}{\frac{i}{2}}, \\ Z_w(i) &= V_w(i) - c \cdot 2^n \binom{n-i}{\frac{d-1}{2}-\frac{i}{2}} \binom{i}{\frac{i}{2}}, \quad w \ge \frac{d}{2}. \end{aligned} \tag{32}$$

We put $w = \omega n$ for the rest of this section.

Proposition 9 *Let C be a code with distance d and dual distance d'. Let*

$$c = \begin{cases} \dfrac{w+1}{2(a-d')} \dfrac{(K_{w+1}(d') + K_w(d'))^2}{(K_{\frac{d-1}{2}}(d'))^2}, & \text{if } 0 \le d' \le n\left(\frac{1}{2} - \sqrt{\omega(1-\omega)}\right), \\ 0, & \text{if } n\left(\frac{1}{2} - \sqrt{\omega(1-\omega)}\right) \le d' \le \frac{n}{2}. \end{cases} \tag{33}$$

Then for sufficiently large n,

$$F_w(d,d') \le |C| \Big[\frac{w+1}{2a} \Big(\binom{n}{w+1} + \binom{n}{w} \Big)^2 - c \binom{n}{\frac{d-1}{2}}^2 \Big] - 2^n \binom{n}{w} + c 2^n \binom{n}{\frac{d-1}{2}}.$$

Proof. To derive the bound, we use the polynomial $Z_w(x)$ (32) in Theorem 1. First let us prove that it is feasible. Using the Christoffel-Darboux formula (43) and (42), we obtain

$$\begin{aligned} v_j &= \binom{n}{w} (K_{w+1}(j) + K_w(j)) \frac{1}{K_w(a)} \sum_{i=0}^{w} \frac{K_i(j) K_i(a)}{\binom{n}{i}} \\ &= \frac{1}{K_w(a)} \binom{n}{w} \sum_{i=0}^{w} \frac{K_i(a)}{\binom{n}{i}} \sum_{s=0}^{n} \Big[p^s_{w+1,i} K_s(j) + p^s_{wi} K_s(j) \Big] \\ &= \sum_{s=0}^{n} \frac{K_s(j)}{K_w(a)} \binom{n}{w} \sum_{i=0}^{w} \frac{K_i(a)}{\binom{n}{i}} (p^s_{w+1,i} + p^s_{wi}). \end{aligned}$$

Again relying on (42), we calculate for integer x

$$\begin{aligned} V_w(x) &= \sum_{j=0}^{n} v_j K_j(x) \\ &= \frac{1}{K_w(a)} \binom{n}{w} \sum_{s=0}^{n} \sum_{i=0}^{w} \frac{K_i(a)}{\binom{n}{i}} (p^s_{w+1,i} + p^s_{w,i}) \sum_{j=0}^{n} K_j(x) K_s(j) \\ &= 2^n \frac{1}{K_w(a)} \binom{n}{w} \sum_{i=0}^{w} \frac{K_i(a)}{\binom{n}{i}} (p^x_{w+1,i} + p^x_{w,i}). \end{aligned}$$

Assume that w and x are even. In other cases the arguments are similar. Estimating the sum in the last expression by the term $i = w$, we have

$$V_w(x) \geq 2^n \binom{n-x}{w-\frac{x}{2}} \binom{x}{\frac{x}{2}}. \tag{34}$$

From this estimate and from the definition of $Z_w(i)$ it follows that

$$Z_w(i) \geq g_w(i), \quad d \leq i \leq n.$$

It remains to prove that $z_i \leq 0$ for $d' \leq i \leq n$. First observe that $z_{d'} = 0$. Indeed, by (44)

$$\sum_{j=0}^{n} (K_{\frac{d-1}{2}}(j))^2 K_j(i) = \sum_j \sum_s p^s_{\frac{d-1}{2}\frac{d-1}{2}} K_s(j) K_j(i) = 2^n p^i_{\frac{d-1}{2}\frac{d-1}{2}}.$$

So the Krawtchouk coefficients in the expansion

$$2^n \binom{n-i}{\frac{d-1}{2}-\frac{i}{2}} \binom{i}{\frac{i}{2}} = \sum_{j=0}^{n} \beta_j K_j(i)$$

are $\beta_j = (K_{\frac{d-1}{2}}(j))^2$. Together with the definition of c (33) this implies that $z_{d'} = 0$. Let us show that $z_j = v_j - c\beta_j \leq 0, d' \leq j \leq n$, for large n. First if $x_1^{(w)} < d'$ then $c = 0$ and $v_j < 0$, so let us assume that $d' \leq x_1^{(w)}$. Note that we only need to consider the values of j in the interval $d' \leq j \leq x_1^{(w)}$ because for greater j by the above we have $v_j < 0$. Since $v_{d'} = c\beta_{d'}$, it suffices to show that for large n the quantity $c\beta_j$ decreases on j slower than v_j.

Observe that $\log v_j \sim 2 \log K_w(j)$ and $\log \beta_j \sim 2 \log K_{d/2}(j)$. For $w > d/2$ we have $x_1^{(w)} \leq x_1^{(d/2)}$, so both polynomials are positive and decline rapidly as j grows. We will prove that for large n the decline rate of $K_{d/2}(j)$ is slower that that of $K_w(j)$. Let $j = \xi n$ and write the derivative of the exponent of $K_w(j)$ in the form $(d/d\xi) \log K_{\omega n}(\xi n) = n\phi(\omega, \xi) + o(n)$. Then from (47) we get

$$\phi(\omega, \xi) = \log \frac{1 - 2\omega + \sqrt{1 - 4\omega + 4\omega^2 - 4\xi + 4\xi^2}}{2 - 2\xi},$$

valid for $0 < \xi < (1/2) - \sqrt{\omega(1-\omega)}$. It is easy to check that for a fixed ξ in this interval, $\phi(\omega, \xi)$ is a decreasing function of ω. Therefore the exponent of v_j is falling faster than that of β_j for $d' \leq j \leq x_1^{(w)}$. This finishes the proof of feasibility of the polynomial (32).

It remains to compute the bound (3). Using (40) and (45), we find $Z_w(0)$ and z_0. Thereby the proof is completed. □

Let us again consider the cases when only d or only d' is known.

5.1 Codes In this case substitution of $d' = 0$ yields a known result. It was obtained in [17], based on a result in [5].

Proposition 10 *Let C be a code with distance $d = \delta n$. Then*

$$a_\xi(\delta, 0) \le H(\xi) - H\left(\frac{\delta}{2}\right) + o(1), \quad \delta \le \xi \le \frac{1}{2}. \tag{35}$$

The proof amounts to a straightforward calculation which we omit. This bound is inferior to (20) and other bounds of this form [17] on the size of a constant weight code.

The following theorem presents a lower bound on $A_{\lfloor \xi n \rfloor}$.

Theorem 11 *For sufficiently large n and any $\omega \ge H^{-1}(1-R)$ there exists $\xi \in [0, 2\omega]$ such that*

$$a_\xi(\delta, 0) \ge 2H(\omega) + R - 1 - (1-\xi)H\Big(\frac{\omega - \xi/2}{1-\xi}\Big) - \xi + o(1). \tag{36}$$

PROOF. Let us choose $Y_w(i) = g_w(i)$. Then by (44) $y_j = (K_w(j))^2$, and $Y_w(i)$ is obviously feasible. Compute

$$\log y_0 = 2nH(\omega), \quad \log Y_w(0) = n(1 + H(\omega))$$

and note that $\frac{1}{n}\log y_0 + R \ge \frac{1}{n}\log Y_w(0)$ for $w = n\omega \ge nH^{-1}(1-R)$. So for such values of w the term $|C|y_0$ grows exponentially faster than $Y_w(0)$. As suggested in the remark after Theorem 1, we have $g_w(i) = 0$ for $i > 2w$, hence there exists an index $i \in [0, 2w]$ such that

$$A_i(d, 0) \ge \frac{|C|y_0}{g_w(i)}(1 - o(1))$$

We conclude by computing logarithms. □

Remark *As a continuation of Example 1, let us observe that the above results imply that the distance distribution of a perfect code is asymptotically binomial:*

$$a_\xi = R + H(\xi) - 1 + o(1), \quad \delta \le \xi \le \frac{1}{2}.$$

This follows by combining the estimates of the two preceding statements. Since nontrivial perfect codes of growing length do not exist, we do not include the details. However, there is some theoretical interest in the fact that the distance distribution of codes that meet in the asymptotics a linear-programming bound, converges to the binomial distribution (this holds true for both instances considered in this paper; this is also true in the Johnson space with respect to the bound (19)).

5.2. Designs. The following bounds on A_j as a function of d' were implicitly obtained in [14].

Theorem 12 [14] *Let C be a code with dual distance $d' = \delta' n$. Then*

$$a_\xi(0,\delta') \leq \begin{cases} R - 1 + H(\xi) + o(1) & \text{if } \frac{(1-2\delta')^2}{2} \leq \xi \leq \frac{1}{2}, \\ R + 2H\left(\frac{1}{2} - \sqrt{\delta'(1-\delta')}\right) - 1 - \xi & \\ \quad -(1-\xi)H\left(\frac{1}{2} - \frac{\sqrt{\delta'(1-\delta')}}{1-\xi}\right) + o(1) & \text{if } 0 \leq \xi < \frac{(1-2\delta')^2}{2}. \end{cases}$$

We will re-derive the first part of this theorem, improve the second part, and as a corollary, extend the interval of binomiality for codes of sufficiently large size. Let

$$\omega^{**} = (1/2)(1 - \sqrt{1-2\xi})$$

and let $q(n)$ be some function of polynomial growth.

First suppose that $\frac{1}{2} - \sqrt{\omega(1-\omega)} \leq \delta'$. Then by (33) $c = 0$ and $Z_w(x) = V_w(x)$. From this we have

$$F_w(0,\delta') \leq |C| v_0 - V_w(0) = q(n)|C|\binom{n}{w}^2 - 2^n\binom{n}{w} < q(n)|C|\binom{n}{w}^2,$$

and

$$a_\xi(0,\delta') \leq R + 2H(\omega) - 1 - (1-\xi)H\left(\frac{\omega - \xi/2}{1-\xi}\right) - \xi + o(1).$$

The optimal choice of ω is $\omega = \omega^{**}$. Hence whenever $0 \leq \frac{1}{2} - \sqrt{\omega^{**}(1-\omega^{**})} \leq \delta'$, or equivalently $\frac{(1-2\delta')^2}{2} \leq \xi \leq \frac{1}{2}$, the following inequality is true:

$$a_\xi(0,\delta') \leq R + 1 - H(\xi) + o(1).$$

This is the first part of Theorem 12.

Now let $\frac{1}{2} - \sqrt{\omega(1-\omega)} \geq \delta'$. Then $c > 0$ and

$$\begin{aligned} F_w(0,d') &\leq |C|\left(q(n)\binom{n}{w}^2 - 2^n c\right) - 2^n\binom{n}{w} + c2^n \\ &\leq q(n)|C|\binom{n}{w}^2 + c2^n. \end{aligned}$$

We obtain

Theorem 13 *Let $0 \leq \xi \leq \frac{(1-2\delta')^2}{2}$. Then for any $\omega \in [\frac{1}{2} - \sqrt{\delta'(1-\delta')}, \frac{1}{2}]$*

$$\begin{aligned} a_\xi(0,\delta') \lesssim & \min\left[R + 2H(\omega), (2/n)\log K_w(d') + 1\right] \\ & - (1-\xi)H\left(\frac{\omega - \xi/2}{1-\xi}\right) - 1 - \xi. \end{aligned}$$

As mentioned above, the interval of binomiality can be extended for sufficiently large codes. Let $\xi_1 = (1-2\delta')^2/2$ and let ξ_2 be the root of the following equation

$$R = (2/n)\log K_{\lfloor n\omega^{**}\rfloor}(\lfloor \delta' n \rfloor) + 1 - 2H(\omega^{**}).$$

If the root of this equation is negative, we put $\xi_2 = 0$.

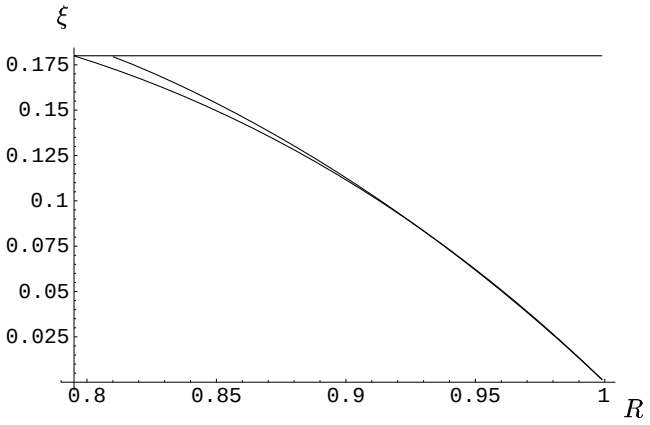


Figure 3: Binomiality range for the distance distribution of codes with $\delta' = 0.2$. The distance distribution is asymptotically binomial in the interval $[\xi(R), 1/2]$; the plot shows the curve $\xi(R)$ from Theorem 12 (straight line) and Corollaries 2, 3.

Corollary 3 *Let C be a code of rate R and dual distance d'. Then for any $\xi \in [\min\{\xi_1, \xi_2\}, 1/2]$ the code C has the binomial distance distribution:*

$$a_\xi(0, \delta') \le R - 1 + H(\xi) + o(1).$$

Example 4 *As mentioned in the end of Sect. 3, the improvement in the estimate of the binomial range over the known results can be substantial. For instance, consider codes with $\delta' = 0.2$. Then Theorem 6 guarantees that the distance distribution is binomial for $0.2 \le \xi \le 1/2$ and Theorem 12 does the same for $0.18 \le \xi \le 1/2$. Corollaries 2 and 3 give much better results for high code rates, see Fig. 3. In this example the binomiality range is extended for code rates $R \in [0.795, 1]$. Corollary 2 gives the best results for $0.795 \le R \le 0.93$; thereafter Corollary 3 gives a slightly wider range of distances.*

Appendix A: Another proof of Theorem 3.

Let d be the code distance and $t = \lfloor n/2 - \sqrt{d(n-d)} \rfloor$. We note that d is approximately equal to the first zero $x_1^{(t)}$ of the Krawtchouk polynomial $K_t(x)$. Let $m, x_1^{(t+1)} < m < x_1^{(t)}$, be the number such that $nK_{t+1}(m) = -K_t(m)$. Such a choice is possible for any n because of the interlacing property of the zeros of K_t and K_{t+1}: $x_1^{(t+1)} < x_1^{(t)} < x_2^{(t+1)}$. Let us define the polynomial $Z(x)$ as follows:

$$Z(x) = \frac{(K_t(x) + nK_{t+1}(x))^2}{x - m}. \tag{37}$$

The Krawtchouk coefficients of $Z(x)$ are nonpositive. Indeed, we have

$$Z(x) = \frac{1}{(K_{t+1}(m))^2} \frac{(K_{t+1}(m)K_t(x) - K_t(m)K_{t+1}(x))^2}{x-m}$$

so this follows by (43). Further, $Z(x) < 0$ for $0 \le x < m$ and $Z(x) \ge 0$ for $m \le x \le n$. Therefore if we take in Theorem 1 $g(i) \equiv Z(i)$, the polynomial $Z(x)$ is feasible with respect to the conditions of the theorem.

Recall that by [23] for any code, $|C| \le -Z(0)/z_0$; so assuming that the rate R of the code is $0 < R < H(1/2 - \sqrt{\delta(1-\delta)})$, we see that the dominating term in the difference $z_0|C| - Z(0)$ is the second one. Hence we can write the estimate on A_w in the form

$$A_w \le \frac{-Z(0)(1-o(1))}{Z(w)}. \tag{38}$$

To compute the bound (3), we find

$$Z(0) = -\frac{1}{m}\binom{n}{t}^2 \left(\frac{n(n-t)}{t+1} + 1\right)^2.$$

To complete the proof we have to estimate $Z(w)$. Note that this problem is essentially different from the standard situation since w is greater than the first zero $x_1^{(t)}$. Therefore, the point w is in the *oscillatory segment* for both K_t and K_{t+1}.

Lemma 14 *Let $x \in [d, n/2]$ be an integer and $\alpha(x) = \binom{n}{x}2^{-n}$. Then*

$$(K_t(x) + K_{t+1}(x))^2 \ge O(1)\binom{n}{t}/\alpha(x) \tag{39}$$

Using this estimate in (38) and taking logarithms, we obtain the exponential bound claimed in the theorem. The rest of this appendix is devoted to the proof of (39).

We begin with the following result from [16].

Lemma 15 [16] *Let $s = 2\sqrt{k(n-k)}$. Then for $k \le n/2$ and integer $t \in \left(\frac{n-s}{2}, \frac{n}{2}\right)$,*

$$(K_k(t))^2 - K_k(t-1)K_k(t+1) \ge \frac{s-n+2x}{s} \frac{(t-1)!(n-t-1)!}{((n/2-1)!)^2} U_k(n/2),$$

where for k even

$$U_k(n/2) = \frac{4k(n-k)}{n^2}\binom{n/2}{k/2}^2,$$

and for k odd

$$U_k(n/2) = 4\binom{n/2-1}{(k-1)/2}^2.$$

First note that, as verified easily using the Stirling formula,

$$\frac{s-n+2x}{s}\frac{(x-1)!(n-x-1)!}{((n/2-1)!)^2}U_k(n/2) = p(n)\frac{\binom{n}{k}}{\alpha(t)},$$

where $p(n)$ is a function of at most polynomial growth in n. So for $k \le n/2$ and $n/2 - \sqrt{k(n-k)} \le t \le n/2 + \sqrt{k(n-k)}$ we have

$$(K_k(t))^2 - K_k(t-1)K_k(t+1) \ge p(n)\frac{\binom{n}{k}}{\alpha(t)},$$

Now since

$$\binom{n}{k}K_t(k) = \binom{n}{t}K_k(t),$$

we obtain for integer $x \le n/2$ and $t \in [n/2 - \sqrt{x(n-x)}, n/2 + \sqrt{x(n-x)}]$

$$(K_t(x))^2 - \frac{(t+1)(n-t+1)}{t(n-t)}K_{t-1}(x)K_{t+1}(x) \ge p(n)\frac{\binom{n}{t}}{\alpha(x)}$$

Thus in the interval considered either

$$(K_t(x))^2 \ge \frac{p(n)}{2}\frac{\binom{n}{t}}{\alpha(x)}$$

or

$$|K_{t-1}(x)K_{t+1}(x)| \ge \frac{p(n)t(n-t)}{2(t+1)(n-t+1)}\frac{\binom{n}{t}}{\alpha(x)}.$$

In the last case, since by (40)

$$\alpha(x)(K_{t-1}(x))^2 \le \|K_{t-1}\|^2 = \binom{n}{t-1},$$

we conclude that

$$\frac{(n-t)}{(t+1)}\frac{\binom{n}{t}}{\alpha(x)} \ge |K_{t+1}(x)|^2 \ge \frac{p^2(n)t(n-t)^2}{4(t+1)^2(n-t+1)}\frac{\binom{n}{t}}{\alpha(x)}.$$

Recall that t is linear in n, so these inequalities imply that $p(n) = O(1)$. Since $(K_t(x))^2 \le \binom{n}{t}/\alpha(x)$, the same conclusion also follows for the first case. Thus at any integer point $n/2 - \sqrt{t(n-t)} \le x \le n/2$ at least one of the following asymptotic equalities holds true:

$$\begin{aligned} |K_t(x)| &= O(1)\|K_t\|/\sqrt{\alpha(x)}, \\ |K_{t+1}(x)| &= O(1)\|K_t\|/\sqrt{\alpha(x)}. \end{aligned}$$

This finishes the proof of (39).

Appendix B: Useful identities.

Let $\{K_k(x)\}$ be the family of Krawtchouk polynomials (11). They are orthogonal on $(0,1,\dots,n)$ with weight $\alpha(i) = \binom{n}{i}/2^n$:

$$\langle K_i, K_j\rangle := \int K_i K_j d\alpha = \delta_{ij}\binom{n}{i} \tag{40}$$

For any polynomial $Z(x) = \sum_{i=0}^n z_i K_i(x)$,

$$z_j = \frac{\langle Z, K_j\rangle}{\langle K_j, K_j\rangle} = 2^{-n}\sum_{i=0}^n Z(i)K_i(j) \tag{41}$$

The following properties are standard:

$$\sum_{i=0}^n K_k(i)K_i(j) = 2^n\delta_{jk} \tag{42}$$

$$K_{t+1}(x)K_t(a) - K_t(x)K_{t+1}(a) = \frac{2(a-x)}{t+1}\binom{n}{t}\sum_{i=0}^t \frac{K_i(x)K_i(a)}{\binom{n}{i}}. \tag{43}$$

$$K_t(x)K_s(x) = \sum_{j=0}^n p_{ts}^j K_j(x) \tag{44}$$

where $p_{ts}^j = \binom{n-j}{(t+s-j)/2}\binom{j}{(t-s+j)/2}$ if $t-s+j$ is even and 0 if it is odd (the equality in (44) is asserted only at $0,1,\dots,n$, regardless of the degree of the polynomial on the left). From (11) we see that

$$K_k(0) = \binom{n}{k}. \tag{45}$$

Polynomial $K_t(x)$ has degree t and its t simple zeros are located between 0 and n. Let $x_1^{(t)}$ be the smallest zero of $K_t(x)$; let $n\to\infty, t\to\infty, k/n < 1/2$. Then [23], [19],

$$x_1^{(t)} = \frac{n}{2} - \sqrt{t(1-t)} + O\big(t^{1/6}\sqrt{n}\big). \tag{46}$$

Let $t = \tau n$, $0 \le x = \xi n \le x_1^{(t)}$. By [7] we have

$$\frac{1}{n}\log K_t(x) = H(\tau) + \int_0^\xi \log\frac{1-2\tau+\sqrt{(1-2\tau)^2-4y(1-y)}}{2-2y}dy + o(1). \tag{47}$$

For $\tau = (1/2) - \sqrt{\xi(1-\xi)}$ this gives

$$\frac{1}{n}\log K_t(x) = \frac{1+H(\tau)-H(\xi)}{2}. \tag{48}$$

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