Divisible minimal codes

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Abstract

Minimal codes are linear codes where all non-zero codewords are minimal, i.e., whose support is not properly contained in the support of another codeword. The minimum possible length of such a k-dimensional linear code over $\mathbb{F}_q$ is denoted by $m(k,q)$. Here we determine $m(7,2)$, $m(8,2)$, and $m(9,2)$, as well as full classifications of all codes attaining $m(k,2)$ for $k \le 7$ and those attaining $m(9,2)$. For $m(11,2)$ and $m(12,2)$ we give improved upper bounds. It turns out that in many cases attaining extremal codes have the property that the weights of all codewords are divisible by some constant $\Delta > 1$. So, here we study the minimum lengths of minimal codes where we additionally assume that the weights of the codewords are divisible by Δ.

1 Introduction

Let $\mathbb{F}_q$ be a finite field of cardinality q and $C \subseteq \mathbb{F}_q^n$ be a linear code. If C has cardinality q^k, then we speak of an $[n,k]_q$-code. A non-zero codeword $c \in C$ is called *minimal* if the *support* $\operatorname{supp}(c) := \{i \mid c_i \neq 0\}$ of c is minimal with respect to inclusion in the set $\{\operatorname{supp}(u) \mid u \in C\backslash\mathbf{0}\}$. The code C is a *minimal code* if all of its non-zero codewords are minimal. One of the many applications of minimal codes is secret sharing, see e.g. [AB98]. An important line of research is the determination of the minimum possible length n of a minimal $[n,k]_q$-code, which we denote by $m(k,q)$. In e.g. [ABNR22, Theorem 2.14] the lower bound $m(k,q) \ge (q+1)(k-1)$ was shown. Here we determine $m(7,2)$, $m(8,2)$, and $m(9,2)$, as well as full classifications of all codes attaining $m(k,2)$ for $k \le 7$ and those attaining $m(9,2)$. For $m(11,2)$ and $m(12,2)$ we give improved upper bounds.

A linear $[n,k]_q$-code is called Δ-divisible if all of its weights are divisible by Δ. For some background we refer e.g. to the recent survey [Kur21]. Minimal codes constructed by concatenation with simplex codes, see e.g. [ABN23, BB23], naturally come with a non-trivial divisibility constant $\Delta > 1$. The unique example attaining $m(2,q) = q$, which geometrically corresponds to the points of a line, is q-divisible. For $k' \le 3$ all minimal binary codes of length $m(2k',2)$ are 2-divisible and for dimension $k = 8$ there are minimal binary codes of length $m(8,2) = 24$ that are 2-divisible while not all examples are of this type. In [Kur23] it was shown that the unique minimal code attaining $m(5,3) = 19$ is 3-divisible. So, at least for the small parameters we have considered here there exist q-divisible examples of minimum possible size $m(k,q)$ whenever the lower bound $(q-1)(k-1)+1$ on the minimum distance, see Theorem 2.(b), is divisible by q.[1] We remark that also some constructions for minimal codes are based on few-weight codes, which often have a non-trivial divisibility constant, see e.g. [MS19, SF20, SL21]. Due to the mentioned possible relations between minimal and divisible codes we introduce the minimum possible length $n = m(k,q;\Delta)$ of a Δ-divisible minimal $[n,k]_q$-code. Here we initiate the study of $m(k,q;\Delta)$ and give bounds and exact values, both computationally and theoretically.

The remaining part of this paper is structured as follows. In Section 2 we state the necessary preliminaries before we study bounds and exact values for $m(k,q;\Delta)$ in Section 3. For the special case of binary minimal codes with trivial divisibility $\Delta = 1$ we study the minimum possible length $m(k,2;1) = m(k,2)$ in Section 4.

[1] The second case where this condition is met, after the first $k = 2$, is at dimension $k = q + 2$.

2 Preliminaries

First we consider the well-known correspondence between (non-degenerated) $[n,k]_q$-codes and multisets of points in the projective space $\mathrm{PG}(k-1,q)$ of cardinality n, i.e., the columns of a generator matrix each generate a point, see e.g. [DS98]. We represent each multiset of points in $\mathrm{PG}(v-1,q)$ by a mapping $M\colon \mathcal{P} \to \mathbb{N}_{\ge 0}$ from the set of points $\mathcal{P}$ in $\mathrm{PG}(v-1,q)$ to the non-negative integers, i.e., to each point P we assign a multiplicity $M(P)$. We extend this notion to arbitrary subspaces S by defining $M(S)$ as the sum over all point multiplicities $M(P)$ for all points P in S. The cardinality of M, i.e., the sum of the multiplicities of all points, is denoted by $\#M$. We say that a multiset M of points is *spanning* if the points with positive multiplicity span the entire ambient space.

Definition 1. *A multiset M of points in a projective space is called a* strong blocking multiset *if for every hyperplane H, we have $\langle S \cap H\rangle = H$.*

If M is the multiset of points associated to a linear code C, then C is minimal iff M is a strong blocking multiset, see e.g. [ABN22, TQLZ21]. Directly from the definition of a strong blocking multiset we can read off that a multiset of points in PG(1, q) is a strong blocking multiset iff it contains every point of the entire projective space. Clearly adding points to a multiset does not destroy the property of being a strong blocking multiset, so that we consider *minimal strong blocking sets* in the following, i.e., set of points that are a strong blocking multiset but such that every proper subset is not a strong blocking multiset. So, in $\mathrm{PG}(1,q)$ the unique minimal strong blocking set is a line, so that

$$m(2,q) = q. \tag{1}$$

Since each linear code associated to the point set of a k-dimensional subspace over $\mathbb{F}_q$ is q-divisible, see e.g. [KK20, Lemma 2.a], we have

$$m(2,q;q) = q \tag{2}$$

for each positive integer Δ. For dimension $k=1$ we clearly have $m(1,q)=1$ and $m(1,q;\Delta)=\Delta$ for all $\Delta \in \mathbb{N}_{\ge 1}$.

The representation of a linear code C by a multiset of points M is pretty useful. If we multiply the multiplicity $M(P)$ of every point P by some positive integer t, the cardinality as well as the divisibility is increased by a factor of t. So, we have

$$m(k,q) \le m(k,q;\Delta) \le \Delta \cdot m(k,q) \tag{3}$$

for all $\Delta \in \mathbb{N}_{\ge 1}$. Our examples for dimensions 1 and 2 show that both bounds can be attained with equality. Similarly, we have

$$m(k,q;\Delta) \le m(k,q;t\cdot\Delta) \le t\cdot m(k,q;\Delta) \tag{4}$$

for all $\Delta, t \in \mathbb{N}_{\ge 1}$. If t is coprime to q, then a t-divisible linear code over $\mathbb{F}_q$ is a t-fold repetition of a smaller code, see e.g. [War81, Theorem 1]. So, we have

$$m(k,q;t\cdot\Delta) = t\cdot m(k,q;\Delta) \tag{5}$$

for all $t \in \mathbb{N}_{\ge 1}$ with $\gcd(q,t)=1$. For binary codes we can consider extension by a parity bit to conclude

$$m(k,2;2) \le m(k,2;1)+1. \tag{6}$$

Given a linear code C the *weight* $\mathrm{wt}(c)$ of a codeword $c \in C$ is the number of non-zero entries. With this, the minimum Hamming distance d of C is the minimum weight over all non-zero codewords of C. If an $[n,k]_q$-code has minimum Hamming distance d then we also speak of an $[n,k,d]_q$-code. We summarize the current knowledge on general bounds for the length n, the minimum (non-zero) weight $w_{\min}$, and the maximum (non-zero) weight $w_{\max}$ of a minimal linear code as follows:

Theorem 2. *For each minimal $[n,k]_q$-code we have*

(a) $n \ge (q+1)(k-1)$*;*

(b) $d = w_{\min} \ge (k-1)(q-1)+1$*; and*

(c) $w_{\max} \le n-k+1$.

Proof. For (a) see e.g. [ABNR22, Theorem 2.14], for (b) see e.g. [HN21, Theorem 23] or [ABNR22, Theorem 2.8], and for (c) see [ABNR22, Proposition 1.5]. □

3 Minimum lengths of divisible minimal codes

In this section we consider the determination of the smallest possible length $n = m(k,q;\Delta)$ of a minimal Δ-divisible $[n,k]_q$-code. For dimensions $k \le 2$ the results are stated easily using the geometric reformulation of linear codes as multisets of points. Clearly, we have $m(1,q;\Delta) = \Delta$ attained by a Δ-fold point. For dimension $k = 2$ each point has multiplicity at least 1 since the code has to be minimal. From Δ-divisibility we conclude that the point multiplicities are pairwise congruent modulo Δ, so that the minimum possible length is attained if all point multiplicities are equal. Thus, we have $m(2,q;\Delta) = \frac{(q+1)\Delta}{q}$ if Δ is divisible by q (attained by a Δ/q-fold line) and $m(2,q;\Delta) = (q+1)\Delta$ (attained by a Δ-fold line). Due to Equation (5) it suffices to consider the cases where Δ does not contain a non-trivial factor t that is coprime to the field size q.

If the divisibility constant is large enough, when considering power of the characteristic only, we can give a precise answer:

Proposition 3. *For $r \ge k-1$ we have $m(k,q;q^r) = q^{r-k+1} \cdot \frac{q^k-1}{q-1}$.*

Proof. Since the code is q^r-divisible we have $d \ge q^r$, so that we can apply the Griesmer bound for the lower bound. An attaining example is given by the q^{r-k+1}-fold full k-space. □

Proposition 4. *For $k \ge 2$ we have $m\big(k,2;2^{k-2}\big) = 2^k-1$.*

Proof. Since the k-dimensional simplex code is 2^{k-1}-divisible and minimal, we have $m\big(k,2;2^{k-2}\big) \le 2^k-1$, so that we assume $n \le 2^k-1$ for the length of an attaining code C. Note that the possible non-zero weights of C are given by $i \cdot 2^{k-2}$ for $1 \le i \le 3$.

If $c \in C$ is a codeword of weight $3 \cdot 2^{k-2}$, then the corresponding residual code C_c has length at most $2^{k-2}-1$ and dimension $k-1$ (since C is minimal). Thus, we have $k \ge 3$ and C_c is 2^{k-3}-divisible with 2^{k-3} as the unique non-zero weight. Since one-weight codes are repetitions of simplex codes, see e.g. [Bon84], C_c can have dimension of at most $k-2$ — contradiction.

So, let a_1 be the number of codewords of weight 2^{k-2} and a_2 be the number of codewords of weight 2^{k-1}. From the first two MacWilliams equations we compute $a_1 + a_2 = 2^k - 1$ and $2n = a_1 + 2a_2$, so that $a_1 = 2^{k+1} - 2 - 2n$, i.e., a_1 is even. Since the code is minimal, the sum of any two different codewords of weight 2^{k-2} has again weight 2^{k-2}, i.e. the codewords of the smallest weight form subcode and we have $a_1 = 2^t - 1$ for some integer t.[2] Thus, we have $t = 0$ and $a_1 = 0$, i.e., we have $d \ge 2^{k-1}$ for the minimum distance and can apply the Griesmer bound for the lower bound $n \ge 2^k - 1$. □

For parameters not covered by these two propositions and dimension $k \ge 3$ we have applied the software `LinCode` for the enumeration of linear codes [BBK21] using the bounds for the minimum and maximum possible weight in Theorem 2 and also using the weight restrictions implied by the divisibility constant Δ. For field sizes $q = 2$ and $q = 3$ we summarize our numerical results in Table 1. With this, $m(k,q;\Delta)$ is completely determined for $k \le 9$ if $q = 2$ and for $k \le 5$ if $q = 3$.

[2] We remark that Δ-divisible linear codes spanned by codewords of weight Δ have been completely classified in [KK23a]. Note that there exists a 2^{k-2}-divisible linear code of length 2^{k-1} and dimension k satisfying $a_1 = 2^k - 2$, $a_2 = 1$. However, this code, corresponding to an affine subspace, is not minimal.

k	4	4	5	5	5	6	6	6	6	7	7	7	7	7
q	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Δ	1	2	1	2	4	1	2	4	8	1	2	4	8	16
$m(k,q;\Delta)$	9	9	13	14	17	15	15	18	36	20	21	26	42	84

k	8	8	8	8	8	8	9	9	9	9	9	9	9	10
q	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Δ	1	2	4	8	16	32	1	2	4	8	16	32	64	4
$m(k,q;\Delta)$	24	24	29	45	90	174	26	27	30	58	96	192	384	31

k	10	10	10	10	3	3	4	4	4	5	5	5	5
q	2	2	2	2	3	3	3	3	3	3	3	3	3
Δ	8	16	32	64	1	3	1	3	9	1	3	9	27
$m(k,q;\Delta)$	60	93	186	366	9	12	14	15	38	19	19	48	116

Table 1: Exact values of $m(k,q;\Delta)$ for small parameters where $q \in \{2,3\}$.

Lemma 5. *For each integer $t \ge 2$ we have $m\big(2t,2;2^{t-1}\big) \le 3 \cdot (2^t-1)$.*

Proof. Consider the linear code C corresponding to three pairwise disjoint t-dimensional subspaces of $\mathrm{PG}(2t-1,2)$. With this, C is an $[3 \cdot (2^t-1), 2t]_2$-code with non-zero weighs $2 \cdot 2^{t-1}$ and $3 \cdot 2^{t-1}$, which is minimal due to the Ashikhmin-Barg condition [AB98]. □

We remark that the constructed projective two-weight code contains to the family SU2 in [CK86]. While equality is attained in Lemma 5 for $t \in \{2,4,5\}$, we have $m(6,2;4) = 18 < 21$.

The interesting codes, i.e. those that cannot be obtained by repetitions of smaller codes, are given by

$$\begin{pmatrix} 11111111111010000 \\ 00000111111101000 \\ 00111000111100100 \\ 01011011001100010 \\ 11100001011100001 \end{pmatrix}$$

attaining $m(5,2;4) = 17$ with weight enumerator $1 + 25x^8 + 6x^{12}$ and an automorphism group of order 720, as well as

$$\begin{pmatrix} 111111111110100000 \\ 000001111111010000 \\ 001110001111001000 \\ 010110110011000100 \\ 111000010111000010 \\ 011011100101000001 \end{pmatrix}$$

attaining $m(6,2;4) = 18$ with weight enumerator $1 + 45x^8 + 18x^{12}$ and an automorphism group of order 2160, see [BE97]. For the first code we remark that the automorphism group is isomorphic to the symmetric group S_6 and has point orbits in $\mathrm{PG}(4,2)$ of sizes 1, 15 and 15. The unique point has multiplicity 2 in the attaining construction and the points in one of the other classes have multiplicity 1. The unique code attaining $m(7,2;8)=42$ is given by

$$\begin{pmatrix}
111111111111111111111110000000000001000000\\
000000000001111111111111111111111100100000\\
000000000110000001111110000011111110010000\\
000000001010001110001110011100011110001000\\
111111111100110010010110101101100110000100\\
000000010011000110110010110110101010000010\\
000000100010011010111001011010100110000001
\end{pmatrix}$$

with weight enumerator $1+45x^{16}+82x^{24}$ and an automorphism group of order 138240. Considered as a multiset of points in $\mathrm{PG}(6,2)$ the automorphism group forms three point orbits of sizes 1, 36, and 90 with point multiplicities 6, 1, and 0, respectively. There are 62 non-isomorphic doubly-even minimal $[29,8]_2$-codes. One example is given by

$$\begin{pmatrix}
11111111111111100000010000000\\
00000001111111111100001000000\\
00011110000111100011100100000\\
00100110111001100101100010000\\
01011011001010101110000001000\\
11001001010011110010100000100\\
01110010010011111001000000010\\
00111000100101011101100000001
\end{pmatrix}$$

with weight enumerator $1+114x^{12}+119x^{16}+22x^{20}$ and an automorphism group of order 3.

There are two non-isomorphic 8-divisible minimal $[45,8]_2$-codes. Both have weight enumerator $1+45x^{16}+210x^{24}$ and are projective two-weight codes, see [CK86] for more details. One example is given by the construction in Lemma 5. The orders of the automorphism groups are 3628800 and 120960. The unique code attaining $m(8,2;32)=174$ is given by

$$\begin{pmatrix}
1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111\\
10000000000000000000000000000000000000000000000000000000000000000000000010000000\\
0000000000000000000000000000000000000000000000011111111111111111111111111111111111111111111111\\
11111111111111111111111111111111111111111111111100000000000000000000000001000000\\
0000000000000000000000000000000111111111111111100000000000000001111111111111111111111111111111\\
10000000000000001111111111111111111111111111111111111111111111000000000000100000\\
0000000000000000000000011111111000000001111111100000000111111110000000000000000000000001111111\\
10000000111111110000000000000000000000001111111100000000111111111111110000010000\\
0000000000000000000000011000000110000001100000011000000110000001100000011111111111111110000001\\
10000011000000110000001111111111111111110000001100000011000000110000011100001000\\
0000000000000000000011000011111100111111000011000000110000111111001111000000000000000110000110\\
00001100001111110011110000000000000001100001100011111100000110001111110100000100\\
0011111111111111111101000101111101000100011101110111011101000100010111111111111111111110001010\\
01110111010001000101110000000000000000110001010010001000111011110111110100000010\\
1100000000000000000011101111011011101110110111101101111011101101111011111111111111111010111110\\
10010001000010010000001111111111111111110100100001010010001000100001011000000001
\end{pmatrix}$$

with weight enumerator $1+69x^{64}+186x^{96}$ and an automorphism group of order 61931520. One of the five codes attaining $m(9,2;2)=27$ is given by

$$\begin{pmatrix}
111111111110000000100000000\\
000001111111111100010000000\\
001110001110011111001000000\\
010110010010101101000100000\\
111000110101100111000010000\\
110011010001110001000001000\\
001100111001001110000000100\\
101010111000011001000000010\\
011111010011011010000000001
\end{pmatrix}$$

with weight enumerator $1+90x^{10}+164x^{12}+84x^{14}+123x^{16}+50x^{18}$ and an automorphism group of order 48. There are 9 non-isomorphic codes attaining $m(9,2;4)=30$. All of them have weight enumerator

$1+190x^{12}+255x^{16}+66x^{20}$. An example with an automorphism group of order 10 is given by

$$\begin{pmatrix}
111111111111111000000100000000\\
000000011111111111000010000000\\
000111100001111000111001000000\\
001011100110011011001000100000\\
011101101010001100011000010000\\
101010110000001101111000001000\\
010011010000110111101000000100\\
111010000011100111001000000010\\
111001001100011101100000000001
\end{pmatrix}.$$

There are 3 non-isomorphic codes attaining $m(9,2;8)=58$. All of them have minimum distance $d=24$. An example with weight enumerator $1+194x^{24}+311x^{32}+6x^{40}$ and an automorphism group of order 384 is given by

$$\begin{pmatrix}
1111111111111111111111111111111000000000000000000100000000\\
0000000000000000000111111111111111111111110000000010000000\\
0000000000001111110000001111110000001111111111100001000000\\
0000000111111000011111111000011000110000110001110000100000\\
0001111000011001111001111111111011110000110111101000010000\\
0110000001110001110000000010111001010101111001011000001000\\
1110001000101110101000110011101010101111000000010000000100\\
0011110001100111100010010000000010100111011110110000000010\\
0001110001110000110000000100111111010111101100001000000001
\end{pmatrix}.$$

The unique code attaining $m(9,2;16)=96$ is given by

$$\begin{pmatrix}
111111111111111111111111111111111111111111111110000000000000000000000000000000000000000100000000\\
000000000000000000000001111111111111111111111111111111111111111111111110000000000000000010000000\\
000000000001111111111110000000000001111111111110000000000011111111111111111111111000000001000000\\
000001111110000001111110000001111110000001111110000011111100000011111100000111111111110000100000\\
011110011110011110011110000110000110000110000110111100111100111100111100110000011000111000010000\\
101110101110101110101110001010001010001010001011011101011101011101011100101000101001011000001000\\
000110110111110011010001001001001111011101001100001101101111001101000111101001100011111000000100\\
110011111010010000100110101100111110001000110100000011001011010011101110110111110010000000010\\
001010000110010010010100011110101111101010111010111101110101101101011100100100100100110000000001
\end{pmatrix}$$

with weight enumerator $1+18x^{32}+472x^{48}+21x^{64}$ and an automorphism group of order 41472. There are two codes attaining $m(10,2;4)=31$. Both have weight enumerator $1+310x^{12}+527x^{16}+186x^{20}$, an automorphism group of order 155, and are distance-optimal. Corresponding generator matrices are given by

$$\begin{pmatrix}
1111111111111110000001000000000\\
0000000111111111110000100000000\\
0001111000011110001110010000000\\
0010111001100110110010001000000\\
0111011010100011000110000100000\\
1010101100000011011110000010000\\
1111010101101011111010000001000\\
1011100000101111100100000000100\\
0111101011001000011010000000010\\
1110110000111000010110000000001
\end{pmatrix} \quad \textit{and} \quad \begin{pmatrix}
1111111111111110000001000000000\\
0000000111111111110000100000000\\
0001111000011110001110010000000\\
0010111001100110110010001000000\\
0111011010100011000110000100000\\
1010101100000011011110000010000\\
0100110100001101111010000001000\\
1110100000111001110010000000100\\
1001010001001011110110000000010\\
0011100111010100011010000000001
\end{pmatrix}.$$

[MS77, Chapter 8] contains a construction of an infinite family of $(2^m-1, 2m)$ cyclic codes with three different nonzero weights is given for odd m. As observed in [CL85, Example 6], choosing $m=5$ yields a 4-divisible minimal $[31,10,12]_2$ three-weight code. For $m(10,2;2)$ we have verified that length 28 cannot be attained. There are three codes attaining $m(10,2;8)=60$, all with weight enumerator $1+270x^{24}+735x^{32}+$

$18x^{40}$. The example with an automorphism group of order 69120 is given by

$$\begin{pmatrix}
1111111111111111111111111111111000000000000000000001000000000\\
0000000000000001111111111111111111111000000000000000100000000\\
0000000111111110000000011111111000000011111110000000010000000\\
0000000000011110000111100001111000111100011111110000001000000\\
0001111111111110000111100110011011001101100110111000000100000\\
0110011001100110011001111001100000000000001111011010000010000\\
1010101000011000001010000010111000110011111011001100000001000\\
1010101011101111100111101001011100010001111110011100000000100\\
1010101110000000100110101111101011111100101111111110000000010\\
1010101000100011111110011010001001000100011000101100000000001
\end{pmatrix}.$$

The unique code attaining $m(10,2;16)=93$ is given by the construction in Lemma 5. It has weight enumerator $1+93x^{32}+930x^{48}$ and an automorphism group of order 59996160.

The unique code attaining $m(10,2;64)=366$ is given by

$$\begin{pmatrix}
11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111\\
11111111111111111111111111111111111111111111111111100000000000000000000000000000000000000000000000000000000000000000000000000000000000\\
00000000000000000000000000000000000000000000000000000000000000000000000000000000001000000000\\
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000011111111111111111111111111111111111111111111\\
11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111\\
11111111111000000000000000000000000000000000000000000000000000000000000000000000000100000000\\
00000000000000000000000000000000000000000000000111111111111111111111111111111111111111111111111100000000000000000000000000000000000000000000\\
00011111111111111111111111111111111111111111111111100000000000000000000000000000000000000000000000111111111111111111111111111111111111\\
11111111111111111111111111111111111111111111111111111111110000000000000000000000000100000000\\
00000000000000000000000000000001111111111111110000000000000000000000000000000000111111111111111100000000000000000000000000000001111111111111\\
11100000000000000000000000000000000111111111111111100000000000000000000000000000001111111111111111000000000000000000000000000000001111\\
11111111111100000000000000000000000000000000111111111111111111111111111111111100000001000000\\
00011111111111111111111111111110000111111111110000000000000111111111111111111111110000000000000011100000000000000011111111111110000111111111\\
11100000000000000000000000000001110000000000000111000000000001111111111111111111111111100000000000000001110000111111111111111111110000\\
11111111111100000000000000001111111111111111000011110000011111110000001111111000000000100000\\
00000000000111111111111111111110000000000000011100000000011110000111111111111111110000000011100000000000000000000000000000011100000000000001\\
11100000000000000000000000011100000000000001110000000000011100001111111111111111000000000111000000000000000000011111111111111111110000\\
00000000111000000000000000000000000000011100000000000111000000001110000000011100000000010000\\
01100111111111111111111111111100110011111111111000000110000001111111111111111111111100000011000000110011111111111110011111111110011001111111\\
11100000011111111111111111100000011000000110000001100000011000000110000000000000000000000001100000011001100111100000000000000011110011\\
00111111111100000000000000000000110011111111001100111111111100000010000000110110001000001000\\
00000000011000000000000000000110000000000011001100001100001100001111111111111111100001100001100001111111111111111110011110011111111110011110\\
01100111000000000000000001100111111001111110011111101111110011111111111111111110011111100111111111111111001110000000000000000000111111\\
11001111001101111111111111111100000000011001100000001100110001100001100000000110100000000100\\
00000000101011111111111111111110111111101110101010001010001010000111111111111111011101110101111111111100000000000111101011101010000000100010\\
10101011100000000000000000110101111110100010001010010000101111101011111111111101000100010100001111110101111111111111111111111111110101010000\\
00010001010100000000000000000000101010111101011111110111010101110111010101111100010101000000000010\\
10101001000000111111111111111110001010100010000000001000010000010100000000000000010001000000101010000000000000001010000001000000101010000100\\
00000000111111111111111111010000010100001001000001010000010100000101111111111110000100100000010101010100000010000000000000000000000101\\
01000010000001111111111111111101010010000000101010001000000000100010000001011010001000000000010001
\end{pmatrix}$$

with weight enumerator $1+141x^{128}+882x^{192}$ and an automorphism group of order 27745320960.

The unique code attaining $m(3,3;3)=12$ is given by

$$\begin{pmatrix}
111111110100\\
000011221010\\
011200022001
\end{pmatrix}$$

with weight enumerator $1+6x^{6}+20x^{9}$ and an automorphism group of order 48. For $m(4,3;3)=15$ there are two attaining non-isomorphic codes. They are two-weight codes with weight enumerator $1+50x^{9}+30x^{12}$ and belong to the families FE1 and FE4 in [CK86]. The unique code attaining $m(4,3;9)=38$ is given by

$$\begin{pmatrix}
11111111111111111111111111111000000001000\\
00000000111111111222222222111111110100\\
00000012000012222000011112000122220010\\
01111200001200111001201110012000000001
\end{pmatrix}$$

with weight enumerator $1+12x^{18}+68x^{27}$ and an automorphism group of order 384. The unique code attaining $m(5,3;9)=48$ is given by

$$\begin{pmatrix}
111111111111111111111111111111111111110000000010000\\
000000000000000001111111112222222222111111111101000\\
000000000111111120000111120111112222000122220010 0\\
000000001011111121011100120201221112122200020001 0\\
000000000200122202012222222122120121002201220000 1
\end{pmatrix}$$

with weight enumerator $1+6x^{18}+92x^{27}+144x^{36}$ and an automorphism group of order 96. The unique code attaining $m(5,3;27)=116$ is given by

$$\begin{pmatrix}
11111111111111111111111111111111111111111111111111111111111111111111111111111111000000000000000000000000000000010000\\
00000000000000000000000000011111111111111111111111111122222222222222222222222222111111111111111111111111110000001000\\
00000000000000011111122222200000011111122222222222222200000011111111111111222222000000111111222222222222221111100100\\
00000000012222012222012222011112011112000000000001111200001200000000000012000012122220122220000000000122220001200010\\
00000000011011222012200000121011212012220000000000012001121100000000122220012000001211011200000000002201221121100001
\end{pmatrix}$$

with weight enumerator $1+30x^{54}+212x^{81}$ and an automorphism group of order 89856.

For $q=4$ also fractional powers of the field size need to be considered. For small parameters we have obtained $m(3,4;1)=12$, $m(3,4;2)=14$, $m(3,4;4)=15$, $m(3,4;8)=21$, $m(4,4;1)=18$, $m(4,4;2)=19$, $m(4,4;4)=20$, $m(4,4;8)=40$, $m(4,4;16)=62$, and $m(4,4;32)=85$. As the number suggest, we have a similar result as Proposition 4 for $q=4$:

Proposition 6. *For $k\ge 2$ we have $m\big(k,4;2^{2k-3}\big)=\frac{4^k-1}{3}$.*

Proof. Since the k-dimensional simplex code is 4^{k-1}-divisible and minimal, we have $m\big(k,4;2^{2k-3}\big)\le\frac{4^k-1}{3}$. The possible non-zero weights of an attaining code C are given by $i\cdot 2^{2k-3}$ for $1\le i\le 2$. By $3a_i$ we denote the corresponding number of codewords, so that the first two MacWilliams equations yield $a_1+a_2=\frac{4^k-1}{3}$ and $2n=a_1+2a_2$. With this, $a_1=2\cdot\frac{4^k-1}{3}-2n$ is even. However, the assumption that C is minimal implies that the sum of any two different codewords with weight $\Delta:=2^{2k-3}$ also has weight Δ. Thus, the codewords of weight Δ form a subcode implying that $a_1=\frac{4^t-1}{3}$ for some integer t.[3] With this we conclude $t=0$ and $a_1=0$, i.e., we have $d\ge 4^{k-1}$ for the minimum distance and can apply the Griesmer bound for the lower bound $n\ge\frac{4^k-1}{3}$. $\square$

4 Minimum lengths of binary minimal codes

As introduced before, we denote by $m(k,q)$ the minimum possible length n of a minimal $[n,k]_q$-code. In this section we will consider binary minimal codes only. The values $m(1,2)=1$, $m(2,2)=3$, $m(3,2)=6$, $m(4,2)=9$, $m(5,2)=13$, and $m(6,2)=15$ are known since a while, see [Slo93]; c.f. also [dCK21, Table 1] and [ABN22]. The bounds $19\le m(7,2)\le 21$, $m(8,2)\le 25$, $m(9,2)\le 29$ were reported in [Slo93].[4] For $m(10,2)\le 30$ we refer to [CZ94, Section II.A]. Constructions from [BB23] yield $m(12,2)\le 42$, $m(15,2)\le 54$, $m(16,2)\le 63$, and [Slo93] states $m(11,2)\le 41$, $m(13,2)\le 51$.

As rigorously analyzed in [Sco23], the lower bound $m(k,q)\ge(q+1)(k-1)$ (see Theorem 2.(a)) cannot be attained if k is sufficiently large since the minimum distance $d\ge(k-1)(q-1)+1=k$ (see Theorem 2.(b)) cannot be attained with equality for $n=(q+1)(k-1)$; c.f. [Slo93, Theorem 4]. Indeed, the data at `www.codetables.de` on possible minimum distances of $[n,k]_2$-codes implies $m(9,2)\ge 26$, $m(10,2)\ge 28$, $m(11,2)\ge 31$, $m(12,2)\ge 34$, $m(13,2)\ge 39$, $m(14,2)\ge 41$, $m(15,2)\ge 45$, and $m(16,2)\ge 47$. We remark that [Sco23] also contains theoretical proofs for $m(k,2)>3(k-1)$ for $k\in\{5,7,8,9,11,13\}$.

Here we determine $m(7,2)=20$, $m(8,2)=24$, and $m(9,2)=26$, as well as full classifications of all codes attaining $m(k,2)$ for $k\le 7$ and those attaining $m(9,2)$. For $m\in\{11,12\}$ we give constructions for the improved upper bounds $m(11,2)\le 35$ and $m(12,2)\le 40$.

For $k\le 4$ the attaining examples are unique up to equivalence and have nice geometric descriptions, i.e., the corresponding strong blocking sets are given by a point, a line, a plane minus a point, and a hyperbolic quadric. Theoretical uniqueness proofs are pretty simple for $k\le 3$ and for $k=4$ we refer to [Sma23]. Alternatively we can describe the example for $k=4$ as the union of three disjoint lines.[5] The next value

[3] We remark that Δ-divisible linear codes spanned by codewords of weight Δ have been completely classified in [KK23a].

[4] The authors of [BDGP23] have determined $m(7,2)=20$ and $m(8,2)\le 24$ via ILP computations – personal communication.

[5] A sketch of a direct uniqueness proof is given as follows. The standard equations for a projective $[n,4]_2$ code with minimum weight 4 and maximum weight $n-3$ yield $n\ge 9$ and weight enumerator $1+9x^4+6x^6$ for $n=9$. Thus, the complement is a 2-divisible projective code of length 6 and dimension k, which has to be the union of two disjoint lines, see e.g. [KK23b, Proposition 17].

$m(5,2) = 13$ is attained by exactly two non-equivalent codes given e.g. by generator matrices

$$\begin{pmatrix} 1111110010000 \\ 0001111101000 \\ 1110010100100 \\ 0010101100010 \\ 0101010100001 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 1111111010000 \\ 0001111101000 \\ 0110011100100 \\ 1010101100010 \\ 0101110000001 \end{pmatrix}.$$

The corresponding weight enumerators and orders of the automorphism groups are given by $1 + 8x^5 + 8x^6 + 4x^7 + 7x^8 + 4x^9$, $1 + 6x^5 + 12x^6 + 4x^7 + 3x^8 + 6x^9$ and 8, 48, respectively. For $m(6,2) = 15$ there is again a unique example given e.g. by the generator matrix

$$\begin{pmatrix} 111111100100000 \\ 000111110010000 \\ 011001101001000 \\ 100011101000100 \\ 001110101000010 \\ 011010110000001 \end{pmatrix}$$

of a BCH code, see [CL85]. This code has weight enumerator $1 + 30x^6 + 15x^8 + 18x^{10}$ and an automorphism group of order 360. For a description of this code as the concatenation of two codes we refer to [BB23].

We remark that all above extremal codes meet the bounds for the minimum weight $w_{\min} \geq (k-1)(q-1)+1 = k$ (see Theorem 2.(b)) and the maximum weight $w_{\max} \leq n-k+1$ (see Theorem 2.(c)). Using these bounds we have applied the software `LinCode` for the enumeration of linear codes [BBK21] to determine $m(7,2) = 20$ and $m(8,2) = 24$. For $k = 7$ there are 33 non-equivalent extremal codes (all with $w_{\min} = 7$ and $w_{\max} = 14$). Generator matrices for those with more than eight automorphisms are given by

$$\begin{pmatrix} 11111111100001000000 \\ 00001111111100100000 \\ 00110011101110010000 \\ 01010101110110001000 \\ 11011000110100000100 \\ 10001000111010000010 \\ 11110010010010000001 \end{pmatrix}, \begin{pmatrix} 11111111100001000000 \\ 00001111111100100000 \\ 00110011101110010000 \\ 01010100111110001000 \\ 10111001110100000100 \\ 11100101110010000010 \\ 11000110100110000001 \end{pmatrix}, \begin{pmatrix} 11111111100001000000 \\ 00001111111100100000 \\ 00110011101110010000 \\ 01010100111110001000 \\ 10111001110110000100 \\ 11101010001100000010 \\ 11001001011010000001 \end{pmatrix}, \begin{pmatrix} 11111111100001000000 \\ 00001111111100100000 \\ 00110011101110010000 \\ 01011101100110001000 \\ 11111100111010000100 \\ 10110100100110000010 \\ 01001101011010000001 \end{pmatrix}.$$

We remark that there are 88010 minimal $[22,7,8]_2$-codes. None of them can be extended to a minimal $[23,8,8]_2$-code. There are e.g. 2778120 minimal $[22,6,8]_2$-codes. Due to the large number of subcodes we have not enumerated all extensions. So far we have enumerated 2459606 minimal $[23,7,8]_2$ and 31994 minimal $[24,8,8]_2$ non-isomorphic codes. One example is given by the generator matrix

$$\begin{pmatrix} 111111111111100010000000 \\ 000000011111111101000000 \\ 000111100011101100100000 \\ 011000100100111100010000 \\ 001001101101110000001000 \\ 000010111000011100000100 \\ 110111100001110000000010 \\ 010001000011110100000001 \end{pmatrix}$$

with weight enumerator $1 + 18x^8 + 30x^9 + 30x^{10} + 30x^{11} + 22x^{12} + 42x^{13} + 42x^{14} + 26x^{15} + 15x^{16}$ and an automorphism group of order 6. (There is also one example with an automorphism group of order 18.) We remark that most of the examples satisfy $w_{\min} = 8$, $w_{\max} = 17$, and all intermediate weights occur. Another example, that is 2-divisible, is given by the generator matrix

$$\begin{pmatrix}
111111111111100010000000\\
000000011111111101000000\\
000111100011101100100000\\
001011100101110100010000\\
011101100110110000001000\\
001110111101011100000100\\
001001101100001100000010\\
101100011100100000000001
\end{pmatrix}$$

and has weight enumerator $1+28x^8+60x^{10}+72x^{12}+68x^{14}+27x^{16}$. So far, we found 258 such non-isomorphic examples.

For dimension $k = 9$ we have slightly changed our algorithmic approach. Using the fact that adding a parity bit to a binary code yields a 2-divisible (also called even) code, we have enumerated all 2-divisible minimal $[n, 9]_2$-codes with $n \le 27$. It turns out that there are exactly 5 such non-isomorphic codes with length $n = 27$ and none with a strictly smaller length. If C is a minimal $[n, 9]_2$-code that is not even, that adding a parity bit yields an even minimal $[n + 1, 9]_2$-code. Inverting this operation, we have deleted a column of the above five codes in all possible ways and obtained 34 non-isomorphic $[26, 9, 9]_2$-codes of which exactly 4 are minimal, i.e., we have $m(9, 2) = 26$. One example is given by

$$\begin{pmatrix}
11111111110000000100000000\\
00001111111111100010000000\\
01110001110011111001000000\\
00110010010101101000100000\\
11010010101100111000010000\\
01110110000010110000001000\\
01101010110110001000000100\\
10011100101001011000000010\\
11001101001100010000000001
\end{pmatrix}$$

with weight enumerator $1 + 32x^9 + 62x^{10} + 64x^{11} + 84x^{12} + 64x^{13} + 44x^{14} + 64x^{15} + 43x^{16} + 32x^{17} + 22x^{18}$ and an automorphism group of order 16.

For dimension $k = 10$ we remark that [CZ94, Section II.A] reports an example verifying $m(10, 2) \le 30$. The idea was to puncture a 4-divisible (cyclic) minimal $[31, 10, 12]_2$ code. In Section 3 we have determined all 4-divisible minimal $[31, 10, 12]_2$ codes. There are exactly two such non-isomorphic codes and also two non-isomorphic puncturings with generator matrices

$$\begin{pmatrix}
111111111111110000001000000000\\
000000111111111110000100000000\\
001111000011110001110010000000\\
010111001100110110010001000000\\
111011010100011000110000100000\\
010101100000011011110000010000\\
111010101101011111010000001000\\
011100000101111100100000000100\\
111101011001000011010000000010\\
110110000111000010110000000001
\end{pmatrix} \text{ and } \begin{pmatrix}
111111111111110000001000000000\\
000000111111111110000100000000\\
001111000011110001110010000000\\
010111001100110110010001000000\\
111011010100011000110000100000\\
010101100000011011110000010000\\
100110100001101111010000001000\\
110100001110011100100000000100\\
001010001001011110110000000010\\
011100111010100011010000000001
\end{pmatrix}.$$

The codes both have an automorphism group of order five and weight enumerator $1 + 120x^{11} + 190x^{12} + 272x^{15} + 255x^{16} + 120x^{19} + 66x^{20}$.

In order to construct small minimal codes in dimensions 11 and 12 we consider a geometric construction. If M is a multiset of points and Q is a point in $\operatorname{PG}(v-1q)$, where $v \geq 2$, then we can construct a multiset M_Q by projection trough Q, that is the multiset image under the map $P \mapsto \langle P, Q\rangle/Q$ setting $M_Q(L/Q) = M(L) - M(Q)$ for every line $L \geq P$ in $\operatorname{PG}(v-1, q)$. We directly verify the following properties:

Lemma 7. *Let M be a strong blocking multiset* $\operatorname{PG}(k-1, q)$*, where $k \geq 2$, and let M_Q arise from M by projection through a point Q. Then we have $\#M_Q = \#M - M(Q)$, the span of M_Q has dimension $k-1$, and M_Q is a strong blocking multiset.*

By M' we denote the set of points that have positive multiplicity in M_Q, so that also M' is a strong blocking (multi-)set in $\operatorname{PG}(k-1, q)/Q \cong \operatorname{PG}(k-2, q)$, i.e., we can reduce points with multiplicity larger than one to multiplicity one. So, starting from a minimal $[n, k]_q$-code C we consider the corresponding multiset of points M, apply projection through a point Q, reduce point multiplicities to obtain M', and then consider the corresponding minimal $[\#M', k]_q$-code C'.

As an example we consider the binary code

$$\begin{pmatrix} 1111110010000 \\ 0001111101000 \\ 1110010100100 \\ 0010101100010 \\ 0101010100001 \end{pmatrix}$$

attaining $m(5, 2) = 13$. Choosing Q as the first column of the generator matrix gives the code C' with generator matrix

$$\begin{pmatrix} 001111101 \\ 001100110 \\ 010101100 \\ 101010100 \end{pmatrix},$$

which is a representation of the unique code attaining $m(4, 2) = 9$, i.e., the union of three disjoint lines. In our examples the lines through column 1 that contain at least three points (which is the maximum for $q = 2$ and projective codes) are given by the triples of column indices $(1, 2, 13)$, $(1, 3, 12)$, and $(1, 9, 11)$. Also choosing the point Q as the second column yields a minimal $[9, 4]_2$-code, while all other columns yield (minimal) codes of larger lengths. For projective binary codes or point sets M in $\operatorname{PG}(k-1, 2)$ the geometric description of the cardinality of M' equals $\#M - 1$ minus the number of full lines through Q. I.e., if Q equals the first or the second column, then there are exactly three full lines through Q, which is the maximum since $m(4, 2) \geq 9$. If Q equals the last column then there is unique full line through Q and there are exactly two full lines through Q in all other cases.

Applying projection to the second non-isomorphic code attaining $m(5, 2) = 13$ yields minimal $[10, 4]_2$- and a minimal $[12, 4]_2$-code. Applying projection to the unique minimal $[9, 4]_2$-code yields the unique minimal $[6, 3]_2$-code in all cases. This continues for dimension three and two, as can be easily seen from the geometric description of the extremal point sets. Applying projection to the unique minimal $[15, 6]_2$-code yields minimal $[13, 5]_2$-codes in all cases (which all have automorphism groups of order 48, i.e. are equivalent to second non-isomorphic $[13, 5]_2$-code). We remark that in [Slo93, Table I] the example for a minimal $[13, 5]_2$-code was described as "omit coordinates 1,6 from" the (unique) minimal $[15, 6]_2$-code. In the same vein a minimal $[29, 9]_2$-code was constructed from a minimal $[31, 10]_2$-code. We remark that applying projection to the minimal $[26,9]_2$-code

$$\begin{pmatrix}
11111111111000000100000000\\
00000111111111100010000000\\
00111000111001111001000000\\
01011001001010101000100000\\
11100011110100011000010000\\
00101111010001110000001000\\
10001100111011001000000100\\
10110101110111111000000010\\
11001001110110100000000001
\end{pmatrix}$$

gives minimal $[n,8]_2$-codes for $n \in \{24,25\}$. This phenomenon also occurs for field sizes larger than 2.

The inversion of the projection transformation gives rise to an integer linear programming formulation to search for minimal codes of small length. Starting with the first minimal $[30,10]_2$ code let us find the following minimal $[35,11]_2$ code with generator matrix

$$\begin{pmatrix}
11011110101100100010110010010101000\\
01000000000011000110110110000011100\\
00110000000101000110111101011100100\\
00001000000010011000011100000010111\\
00000100000101011110111010101110101\\
00000010000111010110010101100000001\\
00000001100011010000111011010010001\\
00000000010001001110010111001110011\\
00000000001111000000001111000001111\\
00000000000000111110000000011111111\\
00000000000000000001111111111111111
\end{pmatrix},$$

weight enumerator $1 + 19x^{11} + 83x^{12} + 142x^{13} + 118x^{14} + 125x^{15} + 194x^{16} + 296x^{17} + 356x^{18} + 237x^{19} + 141x^{20} + 134x^{21} + 102x^{22} + 67x^{23} + 29x^{24} + 4x^{25}$ and a trivial automorphism group. Applying the approach again yields the following minimal $[40,12]_2$ code with generator matrix

$$\begin{pmatrix}
1001110000000101010110100110011101010111\\
0100011001011100100110000000011000111101\\
0000011111001000110010100000011000110010\\
0000001001010111001110010000000100111000\\
0011001101011000111100000000001000001011\\
0000100011010111101000001000010000001101\\
0000010011010011011100000100000100000011\\
0000010111001100111010000010001100001111\\
0000001111000111100110000001000000000001\\
0000000000111100011110000000111100000111\\
0000000000000011111110000000000011111111\\
0000000000000000000001111111111111111111
\end{pmatrix},$$

weight enumerator $1 + 21x^{12} + 70x^{13} + 120x^{14} + 173x^{15} + 183x^{16} + 261x^{17} + 408x^{18} + 493x^{19} + 560x^{20} + 521x^{21} + 408x^{22} + 319x^{23} + 240x^{24} + 167x^{25} + 88x^{26} + 39x^{27} + 19x^{28} + 5x^{29}$ and a trivial automorphism group. We remark that both ILP computations were aborted before finishing.

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