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New pseudo-planar binomials in characteristic two and related schemes

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Abstract Planar functions in odd characteristic were introduced by Dembowski and Ostrom in order to construct finite projective planes in 1968. They were also used in the constructions of DES-like iterated ciphers, error-correcting codes, and signal sets. Recently, a new notion of pseudo-planar functions in even characteristic was proposed by Zhou. These new pseudo-planar functions, as an analogue of planar functions in odd characteristic, also bring about finite projective planes. There are three known infinite families of pseudo-planar monomial functions constructed by Schmidt and Zhou, and Scherr and Zieve. In this paper, three new classes of pseudo-planar binomials are provided. Moreover, we find that each pseudo-planar function gives an association scheme which is defined on a Galois ring.

Keywords Pseudo-planar function · Relative difference set · Projective plane · Association scheme

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1 Introduction

Let $q = p^n$ where p is an odd prime and n is a positive integer. A function $f : \mathbb{F}_q \to \mathbb{F}_q$ is *planar* if the mapping

$$x \to f(x + \epsilon) - f(x) \tag{1}$$

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Table 1 The known pseudo-planar monomials on $\mathbb{F}_{2^n}$

Function	Condition	References
ax^{2^k}	$a \in \mathbb{F}_{2^n}^*$	Trivial
ax^{2^k+1}	$n = 2k$, $a \in \mathbb{F}_{2^{n/2}}^*$, $\mathrm{Tr}_{n/2}(a) = 0$	[20, Theorem 6]
$ax^{4^k(4^k+1)}$	$n = 6k$, $a \in \mathbb{F}_{2^n}^*$, a is a $(4^k - 1)$-th power but not a $3(4^k - 1)$-th power	[19, Theorem 1.1]

is a permutation of $\mathbb{F}_q$ for each $\epsilon \in \mathbb{F}_q^*$. Planar functions were introduced by Dembowski and Ostrom [8] to construct finite projective planes over finite fields with odd characteristic. Apart from this, planar functions emerge from many other applications. In the cryptography literature, they are called *perfect nonlinear functions* [18], and used in the constructions of DES-like iterated ciphers, since they are optimally resistant to differential cryptanalysis. Carlet, Ding, and Yuan [7,9,23], among others, utilized planar functions to construct error-correcting codes, which are then employed to design secret sharing schemes. Planar functions are also applied to the construction of authentication codes [10], constant composition codes [12] and signal sets [11]. Besides, planar functions induce many combinatorial objects such as skew Hadamard difference sets and Paley type partial difference sets [22].

When $p = 2$, there are no planar functions over $\mathbb{F}_{2^n}$, since if x satisfies $f(x+\epsilon) - f(x) = d$, then so does $x + \epsilon$. As an alternative, a function $f : \mathbb{F}_{2^n} \to \mathbb{F}_{2^n}$ is said to be *almost perfect nonlinear* if the mapping (1) is 2-to-1 for every $\epsilon \in \mathbb{F}_{2^n}^*$. However, there is no apparent link between almost perfect nonlinear functions and finite projective planes. Recently, Zhou [24] put forward a definition of "planar" functions over finite fields with characteristic two, which give rise to finite projective planes. From now on, we call a function $f : \mathbb{F}_{2^n} \to \mathbb{F}_{2^n}$ *pseudo-planar* if

$$x \to f(x+\epsilon) + f(x) + \epsilon x$$

is a permutation on $\mathbb{F}_{2^n}$ for each $\epsilon \in \mathbb{F}_{2^n}^*$. Note that Zhou [24] called such functions "planar", and the term "pseudo-planar" was first used by Abdukhalikov [1] to avoid confusion with planar functions in odd characteristic.

The pseudo-planar monomial functions have been investigated by Schmidt and Zhou [20], and Scherr and Zieve [19]. They are listed in Table 1, where $\mathrm{Tr}_{n/2}$ denotes the trace function from $\mathbb{F}_{2^{n/2}}$ to $\mathbb{F}_2$. In this paper, we construct three new classes of pseudo-planar binomial functions, at least two of them are infinite families. Association schemes form a central part of algebraic combinatorics, and play important roles in several branches of mathematics, such as coding theory and graph theory. One interesting result we obtained is that pseudo-planar functions will always give 5-class association schemes which are defined on Galois rings. Our construction can be regarded as an analogue of the one studied by Liebler and Mena [16], and Bonnecaze and Duursma [5]. Similar (but symmetric) 4-class association schemes were constructed by Abdukhalikov, Bannai and Suda [2], and LeCompte, Martin and Owens [14]. Analogous to the case of almost perfect nonlinear functions, we define the Fourier spectrum of pseudo-planar functions. With the information obtained from eigenmatrices of those association schemes, we completely determine the Fourier spectrum.

The rest of this paper is organized as follows. Section 2 contains the background of the mathematical objectives involved. Section 3 presents the construction of three classes of pseudo-planar binomial functions. Section 4 investigates the association schemes arising from pseudo-planar functions. Section 5 concludes this paper.

2 Preliminaries

2.1 Relative difference sets and the inversion formula

Let G be a finite abelian group and let N be a subgroup of G. A subset D of G is a *relative difference set (RDS)* with parameters $(|G|/|N|, |N|, |D|, \lambda)$ and *forbidden subgroup* N if the list of nonzero differences of D comprises every element in $G\backslash N$ exactly λ times, and no element of $N\backslash\{0\}$. The *group ring* $\mathbb{Z}[G]$ is a free abelian group with a basis $\{g \mid g \in G\}$. For any set A whose elements belong to G (A may be a multiset), we identify A and the group ring element $\sum_{g\in A} d_g g$ throughout the rest of the paper, where d_g is the multiplicity of g appears in A. Given any $A = \sum d_g g \in \mathbb{Z}[G]$, we define $A^{(-1)} = \sum d_g g^{-1}$, in which g^{-1} is the inverse of g with respect to the operation of group G. Using the language of group ring, a relative difference set D in G with forbidden group N can be expressed in a succinct way:

$$DD^{(-1)} = |D|1_G + \lambda(G - N),$$

where 1_G is the identity of group G.

For a finite abelian group G, denote its character group by $\widehat{G}$. For any $A = \sum d_g g$ and $\chi \in \widehat{G}$, define $\chi(A) = \sum d_g \chi(g)$. The following *inversion formula* shows that A is completely determined by its character value $\chi(A)$, where χ ranges over $\widehat{G}$. For convenience, we will denote d_{1_G} by $[A]_0$ throughout this paper.

Lemma 2.1 *Let G be an abelian group. If $A = \sum_{g\in G} d_g g \in \mathbb{Z}[G]$, then*

$$d_h = \frac{1}{|G|} \sum_{\chi\in\widehat{G}} \chi(A)\chi(h^{-1}),$$

for all $h \in G$. In particular, we have

$$[A]_0 = \frac{1}{|G|} \sum_{\chi\in\widehat{G}} \chi(A).$$

2.2 Galois rings

We give a brief introduction to the *Galois ring* $GR(4, n)$. Let $R = GR(4, n)$, then the additive group of R can be identified with the abelian group $(\mathbb{Z}_4^n, +)$. Let $Z = \{2x \mid x \in R\}$, then Z consists of 0 and the zero divisors of R, where 0 is the identity with respect to the addition. The unit group $R\backslash Z$ contains a cyclic subgroup of order $2^n - 1$ generated by an element ξ. The set $T = \{\xi^i \mid 0 \le i \le 2^n - 2\} \cup \{0\}$ is called *Teichmüller system*. For any $x \in R$, there exists a unique representation

$$x = a + 2b, \tag{2}$$

where $a, b \in T$. For any $x \in R$, write $\sqrt{x}$ for $x^{2^{n-1}}$. If we define the addition on T by

$$x \oplus y = x + y + 2\sqrt{xy},$$

then $(T, \oplus, \cdot)$ is a finite field with 2^n elements. Hence, a pseudo-planar function over $\mathbb{F}_{2^n}$ can also be identified with a function from T into itself. For any $x \in R$, we have $x = a + 2b$ for some $a, b \in T$. The map

$$\sigma : a + 2b \mapsto a^2 + 2b^2$$

is the Frobenius map of R, which is a ring automorphism. For any $a \in R$, the trace function of R is the map $\mathrm{Tr} : R \to \mathbb{Z}_4$ defined by

$$\mathrm{Tr}(a) = \sum_{i=0}^{n-1} \sigma^i(a).$$

Let $\mathbf{i} = \sqrt{-1}$. For any $a \in R$, define the map $\chi_a : R \to \mathbb{C}$ by

$$\chi_a(x) = \mathbf{i}^{\mathrm{Tr}(ax)}, \quad \forall x \in R.$$

Then the character group $\widehat{R} = \{\chi_a \mid a \in R\}$. For more information on Galois rings, please refer to [13,16,21].

2.3 Association schemes

Let X be a nonempty finite set. Let $R_0, R_1, \ldots, R_d$ be a partition of $X \times X$ satisfying that

(i) $R_0 = \{(x, x) \mid x \in X\}$;
(ii) for any $0 \le i \le d$, there exists $0 \le i' \le d$ such that $R_{i'} = \{(y, x) \mid (x, y) \in R_i\}$.

For each R_i, its adjacency matrix is denoted by A_i, whose (x, y)-th entry is 1 if $(x, y) \in R_i$ and 0 otherwise. We call $(X, \{R_i\}_{i=0}^d)$ a *d-class association scheme* if there exist nonnegative integers $p_{i,j}^k$ such that

$$A_i A_j = \sum_{k=0}^{d} p_{i,j}^k A_k,$$

where $0 \le i, j, k \le d$.The $\mathbb{C}$-linear span of $A_0, A_1, \ldots, A_d$ forms a semisimple algebra of dimension $d + 1$. Hence, there exists another basis $\{E_0, E_1, \ldots, E_d\}$ consisting of pairwise orthogonal idempotents. So we have

$$A_i = \sum_{j=0}^{d} P_{ji} E_j$$

and

$$E_i = \frac{1}{|X|} \sum_{j=0}^{d} Q_{ji} A_j$$

for certain complex numbers P_{ji}, Q_{ji}. The matrix $P = (P_{ji})$ (resp. $Q = (Q_{ji})$) is called the first (resp. second) eigenmatrix. Clearly, we have $PQ = |X|I$, where I denotes the identity matrix of order $|X|$.

Let $\{S_i \mid 0 \le i \le d\}$ be a partition of X. It induces a partition $\{R_i \mid 0 \le i \le d\}$ on $X \times X$ with

$$R_i = \{(x, y) \mid x - y \in S_i\}.$$

If $(X, \{R_i\}_{i=0}^d)$ forms an association scheme, then we call $(X, \{S_i\}_{i=0}^d)$ a *Schur ring*.

Assume that $(X, \{S_i\}_{i=0}^d)$ is a Schur ring. There is an equivalence relation defined on the character group $\widehat{X}$ of X as follows: $\chi \sim \chi'$ if and only if $\chi(S_i) = \chi'(S_i)$ for each $0 \le i \le d$. Denote by $T_0, T_1, \ldots, T_d$ the equivalence classes, with T_0 consisting of only the principal character. Then $(\widehat{X}, \{T_i\}_{i=0}^d)$ also forms a Schur ring, called the *dual* of $(X, \{S_i\}_{i=0}^d)$. The first eigenmatrix of the dual scheme is equal to the second eigenmatrix of the original scheme. Please refer to [4] or [6] for more details.

We shall need the following well-known criterion due to Bannai [3] and Muzychuk [17].

Theorem 2.2 (Bannai-Muzychuk criterion) *Let P be the first eigenmatrix of an association scheme $(X, \{R_i\}_{0\leq i\leq d})$, and $\Lambda_0 := \{0\}, \Lambda_1, \dots, \Lambda_{d'}$ be a partition of $\{0, 1, \dots, d\}$. Then $(X, \{R_{\Lambda_i}\}_{0\leq i\leq d'})$ forms an association scheme if and only if there exists a partition $\{\Delta_i\}_{0\leq i\leq d'}$ of $\{0, 1, 2, \dots, d\}$ with $\Delta_0 = \{0\}$ such that each (Δ_i, Λ_j)-block of P has a constant row sum. Moreover, the constant row sum of the (Δ_i, Λ_j)-block is the (i, j)-th entry of the first eigenmatrix of the fusion scheme.*

3 Pseudo-planar binomials

It is well-known that every function from $\mathbb{F}_{2^n}$ to itself can be uniquely written as a polynomial function of degree at most $2^n - 1$. The monomial functions $x \mapsto cx^t$ for some $c \in \mathbb{F}_{2^n}$ and some integer t are the simplest nontrivial polynomial functions. An integer t satisfying that $1 \leq t \leq 2^n - 1$ is a *pseudo-planar exponent* of $\mathbb{F}_{2^n}$ if the function $x \mapsto cx^t$ is pseudo-planar on $\mathbb{F}_{2^n}$ for some $c \in \mathbb{F}_{2^n}^*$. The pseudo-planar monomials were first investigated by Schmidt and Zhou [20], and subsequently by Scherr and Zieve [19]. Moreover, in [20, Conjecture 8], it is conjectured that the only exponents that give pseudo-planar monomials are those listed in Table 1.

Besides pseudo-planar monomial functions, the next simplest cases are pseudo-planar binomials. In this section, we construct three classes of pseudo-planar binomials on the field $\mathbb{F}_{2^{3m}}$. The following result will be useful.

Lemma 3.1 ([15, p. 362]) *Let q be a prime power and $\mathbb{F}_{q^r}$ be an extension of $\mathbb{F}_q$. Then the linearized polynomial*

$$L(x) = \sum_{i=0}^{r-1} c_i x^{q^i} \in \mathbb{F}_{q^r}[x]$$

is a permutation of $\mathbb{F}_{q^r}$ if and only if

$$\det \begin{pmatrix} c_0 & c_{r-1}^q & c_{r-2}^{q^2} & \cdots & c_1^{q^{r-1}} \\ c_1 & c_0^q & c_{r-1}^{q^2} & \cdots & c_2^{q^{r-1}} \\ c_2 & c_1^q & c_0^{q^2} & \cdots & c_3^{q^{r-1}} \\ \vdots & \vdots & \vdots & & \vdots \\ c_{r-1} & c_{r-2}^q & c_{r-3}^{q^2} & \cdots & c_0^{q^{r-1}} \end{pmatrix} \neq 0.$$

Let m be a positive integer. The relative trace (resp. norm) from $\mathbb{F}_{2^{3m}}$ to $\mathbb{F}_{2^m}$ is denoted by Tr_3 (resp. N_3) from now on.

Proposition 3.2 *Suppose m is an even positive integer, then the function*

$$f(x) = a^{2^{2m}+1} x^{2^{2m}+1} + a^{-(2^m+1)} x^{2^m+1}$$

is pseudo-planar on $\mathbb{F}_{2^{3m}}$ if and only if

$$\mathrm{Tr}_3((a^{2^{2m}+2^m} + a^{-2^{2m}-2^m-2})(a^{2^m+1} + \epsilon^{2^m-1})\epsilon^{2^m+2} + a^{2^m-2^{2m}}\epsilon^3 + \epsilon) \neq 0$$

for all $\epsilon \in \mathbb{F}_{2^{3m}}^*$.

Proof Set $t = 2^m$. For each $\epsilon \in \mathbb{F}_{2^{3m}}^*$,

$$f(x+\epsilon) + f(x) + \epsilon x = a^{t^2+1}\epsilon x^{t^2} + a^{-(t+1)}\epsilon x^t + (a^{t^2+1}\epsilon^{t^2} + a^{-(t+1)}\epsilon^t + \epsilon)x + (a\epsilon)^{t^2+1} + (a^{-1}\epsilon)^{t+1}.$$

Then it suffices to show that the polynomial

$$G_\epsilon(x) := a^{t^2+1}\epsilon x^{t^2} + a^{-(t+1)}\epsilon x^t + (a^{t^2+1}\epsilon^{t^2} + a^{-(t+1)}\epsilon^t + \epsilon)x$$

is a permutation on $\mathbb{F}_{2^{3m}}$ for any $\epsilon \in \mathbb{F}_{2^{3m}}^*$. By Lemma 3.1, we see that $G_\epsilon(x)$ is a permutation if and only if

$$\det\begin{pmatrix} a^{t^2+1}\epsilon^{t^2} + a^{-(t+1)}\epsilon^t + \epsilon & a^{t+1}\epsilon^t & a^{-(t^2+1)}\epsilon^{t^2} \\ a^{-(t+1)}\epsilon & a^{t+1}\epsilon + a^{-(t^2+t)}\epsilon^{t^2} + \epsilon^t & a^{t^2+t}\epsilon^{t^2} \\ a^{t^2+1}\epsilon & a^{-(t^2+t)}\epsilon^t & a^{t^2+t}\epsilon^t + a^{-(t^2+1)}\epsilon + \epsilon^{t^2} \end{pmatrix}$$
$$\begin{aligned}
=&\mathrm{Tr}_3((a^{t^2+t} + a^{-t^2-t-2})(a^{t+1} + \epsilon^{t-1})\epsilon^{t+2} + a^{t-t^2}\epsilon^3 + \epsilon) \\
=&\mathrm{Tr}_3((a^{2^{2m}+2^m} + a^{-2^{2m}-2^m-2})(a^{2^m+1} + \epsilon^{2^m-1})\epsilon^{2^m+2} + a^{2^m-2^{2m}}\epsilon^3 + \epsilon) \\
\neq& 0.
\end{aligned}$$

This finishes the proof. □

Remark 3.3 We are unable to simplify the necessary and sufficient conditions in Proposition 3.2 to provide a more concise criterion. We also cannot decide whether this construction will give infinite families of pseudo-planar binomials or not.

Here we give two examples. For any $a \in \mathbb{F}_{2^n}^*$, denote the multiplicative order of a by $\mathrm{ord}\,(a)$.

Example 3.4 When $m = 2$, direct computation via computer program shows that

$$f(x) = a^{17}x^{17} + a^{-5}x^5$$

is pseudo-planar on $\mathbb{F}_{2^{3m}}$ if and only if $\mathrm{ord}\,(a) \in \{9, 63\}$, which coincides with the condition in Proposition 3.2.

Example 3.5 When $m = 4$, direct computation via computer program shows that

$$f(x) = a^{257}x^{257} + a^{-17}x^{17}$$

is pseudo-planar on $\mathbb{F}_{2^{3m}}$ if and only if $\mathrm{ord}\,(a) \in \{9, 63, 117, 819\}$, which coincides with the condition in Proposition 3.2.

In the following of this section, we give two infinite families of pseudo-planar binomials.

Let m be a positive integer. Suppose $\epsilon \in \mathbb{F}_{2^{3m}}^* \backslash \mathbb{F}_{2^m}$ and its minimal polynomial over $\mathbb{F}_{2^m}$ is

$$C_\epsilon(x) = x^3 + B_1x^2 + B_2x + B_3 \in \mathbb{F}_{2^m}[x] \quad (B_3 \neq 0).$$

Denote the three roots of $C_\epsilon(x)$ by $x_1(=\epsilon)$, $x_2(=\epsilon^{2^m})$, and $x_3(=\epsilon^{2^{2m}})$. It follows that

$$\begin{aligned}
B_1 =& x_1 + x_2 + x_3 = \mathrm{Tr}_3(\epsilon), \\
B_2 =& x_1x_2 + x_1x_3 + x_2x_3, \\
B_3 =& x_1x_2x_3 = \mathrm{N}_3(\epsilon).
\end{aligned}$$

We can verify that

$$\begin{aligned}\mathrm{Tr}_3(\epsilon^3) =& x_1^3 + x_2^3 + x_3^3\\ =&(x_1+x_2+x_3)^3 + x_1x_2x_3 + (x_1+x_2+x_3)(x_1x_2+x_1x_3+x_2x_3)\\ =&B_1^3 + B_3 + B_1B_2,\\ \mathrm{Tr}_3(\epsilon^{1+2^{m+1}}) =&\mathrm{Tr}_3(x_1x_2^2) = x_1x_2^2 + x_2x_3^2 + x_3x_1^2.\end{aligned}$$

Set $u_1 = \mathrm{Tr}_3(x_1x_3^2)$ and $u_2 = \mathrm{Tr}_3(x_1x_2^2)$. Then we have

$$u_1 + u_2 = B_3 + B_1B_2, \tag{3}$$

$$u_1u_2 = B_1^3B_3 + B_2^3 + B_3^2. \tag{4}$$

We would like to point out that part of the following proof for Proposition 3.6 with $m \equiv 1 \pmod 3$ is provided by one of the anonymous referee and communicated with the Associate Editor.

Proposition 3.6 *Let m be a positive integer and $m \not\equiv 2 \pmod 3$. Then*

$$f(x) = x^{2^m+1} + x^{2^{2m}+2^m}$$

is pseudo-planar on $\mathbb{F}_{2^{3m}}$.

Proof A similar analysis as the proof of Proposition 3.2 shows that f is pseudo-planar if and only if

$$\mathrm{N}_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3 + \epsilon^{1+2^{m+1}}) \neq 0$$

for every $\epsilon \in \mathbb{F}_{2^{3m}}^*$. For convenience, we write $M_\epsilon = \mathrm{N}_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3 + \epsilon^{1+2^{m+1}})$.

First suppose $\epsilon \in \mathbb{F}_{2^m}^*$. Then $M_\epsilon = \mathrm{N}_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3+\epsilon^3) = \mathrm{N}_3(\epsilon) \neq 0$.

Now let $\epsilon \in \mathbb{F}_{2^{3m}}^* \backslash \mathbb{F}_{2^m}$. It can be verified that

$$M_\epsilon = B_1^3 + B_1B_2 + u_2.$$

We will split our consideration into two parts according to whether $B_1 = 0$ or not.

Suppose $B_1 = 0$. Then $M_\epsilon = u_2$. Now if $M_\epsilon = 0$, from (4), we get $B_3 = B_2^{3/2}$. Therefore $B_2 \neq 0$, since otherwise $B_1 = B_2 = B_3 = 0$, which is impossible. Replace $B_3 = B_2^{3/2}$ into $C_\epsilon(x)$, we obtain

$$\left(\frac{\epsilon}{B_2^{1/2}}\right)^3 + \frac{\epsilon}{B_2^{1/2}} + 1 = 0,$$

which implies that

$$\frac{\epsilon}{B_2^{1/2}} \in \mathbb{F}_{2^3}.$$

That is to say that $\epsilon = b\beta$ with $\beta := B_2^{1/2} \in \mathbb{F}_{2^m}^*$ and $b := \epsilon/B_2^{1/2} \in \mathbb{F}_{2^3}^*$. If $m \equiv 0 \pmod 3$, then $b \in \mathbb{F}_{2^3}^* \subseteq \mathbb{F}_{2^m}$, so $\epsilon \in \mathbb{F}_{2^m}$, which is a contradiction. If $m \equiv 1 \pmod 3$, we see that $2^m \equiv 2 \pmod 7$ and $2^{m+1} \equiv 2^{2m} \equiv 4 \pmod 7$. Then

$$\begin{aligned}\mathrm{Tr}_3(\epsilon^3) =&\mathrm{Tr}_3((b\beta)^3) = \beta^3\mathrm{Tr}_3(b^3),\\ \mathrm{Tr}_3(\epsilon^{1+2^{m+1}}) =&\mathrm{Tr}_3(b^{1+2^{m+1}}\beta^{1+2^{m+1}}) = \beta^3\mathrm{Tr}_3(b^5) = \beta^3\mathrm{Tr}_3(b^3).\end{aligned}$$

Hence

$$M_\epsilon = \mathrm{N}_3(\epsilon) + \mathrm{Tr}_3((b\beta)^3 + (b\beta)^{1+2^{m+1}}) = \mathrm{N}_3(\epsilon) \neq 0$$

which is a contradiction.

Next suppose $B_1 \neq 0$. Without loss of generality we let $B_1 = 1$. Assume that $M_\epsilon = 1 + B_2 + u_2 = 0$, then $u_2 = B_2 + 1$. Replace it in (3) and (4), we get $u_1 = B_3 + 1$, and

$$B_2^3 + B_3^2 + B_2 B_3 + B_2 + 1 = 0. \tag{5}$$

If $B_2 = 0$, then $B_3 = 1$, and

$$\epsilon^3 + \epsilon^2 + 1 = 0.$$

Similarly as above, this finally leads to $M_\epsilon = \mathrm{N}_3(\epsilon) \neq 0$, which contradicts the assumption that $M_\epsilon = 0$. If $B_2 \neq 0$, we write $w = (B_3 + 1)/B_2$. Then (5) becomes $B_2 = w^2 + w$. Hence $B_3 = B_2 w + 1 = w^3 + w^2 + 1$. We rewrite $C_\epsilon(x)$ as

$$x^3 + x^2 + (w^2 + w)x + (w^3 + w^2 + 1) = 0. \tag{6}$$

Let the three roots of the polynomial $x^3 + x + 1$ in $\mathbb{F}_{2^m}$ be τ_1, $\tau_2 (= \tau_1^2)$, and $\tau_3 (= \tau_1^4)$. We compute that

$$\begin{aligned}
&(\tau_2 + \tau_1 w + 1)^3 + (\tau_2 + \tau_1 w + 1)^2 + B_2(\tau_2 + \tau_1 w + 1) + B_3 \\
&\quad = (\tau_1^3 + \tau_1 + 1)w^3 + (\tau_2\tau_1^2 + \tau_2 + \tau_1)w^2 + (\tau_2^2\tau_1 + \tau_2 + \tau_1 + 1)w + \tau_2^3 + \tau_2 + 1 \\
&\quad = 0.
\end{aligned}$$

Therefore the element $\tau_2 + \tau_1 w + 1$ is a root of $C_\epsilon(x)$. If $m \equiv 0 \pmod 3$, then τ_i $(1 \leq i \leq 3) \in \mathbb{F}_{2^3} \subseteq \mathbb{F}_{2^m}$ and hence $\tau_2 + \tau_1 w + 1 \in \mathbb{F}_{2^m}$. This contradicts the fact that $C_\epsilon(x)$ is irreducible over $\mathbb{F}_{2^m}$. If $m \equiv 1 \pmod 3$, we see that

$$\begin{aligned}
\mathrm{Tr}_3(\epsilon^3) &= \mathrm{Tr}_3((\tau_2 + \tau_1 w + 1)^3) \\
&= (\tau_2 + \tau_1 w + 1)^3 + (\tau_2 + \tau_1 w + 1)^{3\cdot 2^m} + (\tau_2 + \tau_1 w + 1)^{3\cdot 2^{2m}} \\
&= (\tau_2 + \tau_1 w + 1)^3 + (\tau_3 + \tau_2 w + 1)^3 + (\tau_1 + \tau_3 w + 1)^3 \\
&= (\tau_1^3 + \tau_2^3 + \tau_3^3)w^3 + (\tau_1^2\tau_2 + \tau_2^2\tau_3 + \tau_3^2\tau_1 + \tau_1^2 + \tau_2^2 + \tau_3^2)w^2 \\
&\quad + (\tau_1\tau_2^2 + \tau_2\tau_3^2 + \tau_3^2\tau_1^2 + \tau_1 + \tau_2 + \tau_3)w + (\tau_1^3 + \tau_2^3 + \tau_3^3 + \tau_1^2 + \tau_2^2 \\
&\quad + \tau_3^2 + \tau_1 + \tau_2 + \tau_3 + 1) = w^3 + w^2, \\
\mathrm{Tr}_3(\epsilon^{1+2^{m+1}}) &= \mathrm{Tr}_3((\tau_2 + \tau_1 w + 1)^{1+2^{m+1}}) \\
&= \mathrm{Tr}_3((\tau_2 + \tau_1 w + 1)(\tau_1 + \tau_3 w^2 + 1)) \\
&= (\tau_1\tau_2 + \tau_2\tau_3 + \tau_3\tau_1)w^3 + (\tau_1\tau_2 + \tau_2\tau_3 + \tau_3\tau_1 + \tau_1 + \tau_2 + \tau_3)w^2 \\
&\quad + (\tau_1^2 + \tau_2^2 + \tau_3^2 + \tau_1 + \tau_2 + \tau_3)w + (\tau_1\tau_2 + \tau_2\tau_3 + \tau_3\tau_1 + 1) \\
&= w^3 + w^2.
\end{aligned}$$

Thus

$$M_\epsilon = \mathrm{N}_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3 + \epsilon^{1+2^{m+1}}) = \mathrm{N}_3(\epsilon) \neq 0,$$

which is also a contradiction. □

Remark 3.7 Let $m \equiv 2 \pmod 3$. Suppose $\epsilon \in \mathbb{F}_{2^{3m}}$ satisfying $\epsilon^3 + \epsilon^2 + 1 = 0$. (It is not hard to show that such ϵ exists.) Then we can compute $M_\epsilon = N_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3 + \epsilon^{1+2^{m+1}}) = \sum_{i=0}^{6} \epsilon^i = 0$. Thus $f(x) = x^{2^m+1} + x^{2^{2m}+2^m}$ is not pseudo-planar on $\mathbb{F}_{2^{3m}}$.

Proposition 3.8 *Let m be a positive integer and $m \not\equiv 1 \pmod 3$. Then*

$$f(x) = x^{2^{2m}+1} + x^{2^{2m}+2^m}$$

is pseudo-planar on $\mathbb{F}_{2^{3m}}$.

Proof A similar analysis to the proof of Proposition 3.2 shows that f is pseudo-planar if and only if

$$\mathrm{N}_3(\epsilon) + \mathrm{Tr}_3(\epsilon^3 + \epsilon^{2+2^m}) \neq 0$$

for every $\epsilon \in \mathbb{F}^*_{2^{3m}}$. The remaining discussion is analogous to Proposition 3.6. □

4 Association schemes arising from pseudo-planar functions

Let $R = GR(4, n)$ be a Galois ring. For any set A whose elements belong to R (A may be a multiset), we identify A and the group ring element $\sum_{g\in A} d_g g \in \mathbb{Z}[R]$ throughout this section, where d_g is the multiplicity of $g \in A$. It is well known that the Teichmüller system T is a $(2^n, 2^n, 2^n, 1)$-RDS in R with respect to Z, where

$$Z = \{2x \mid x \in R\}.$$

Bonnecaze and Duursma in [5] showed that T gives rise to an association scheme. More specifically, when $n \geq 3$, we have four disjoint subsets

$$\Omega_0 = \{0\},\ \Omega_1 = T^*,\ \Omega_2 = \{-x \mid x \in \Omega_1\},\ \Omega_3 = Z\backslash\{0\},$$

where $T^* := T\backslash\{0\}$. The rest elements of R are divided into two classes. Let Ω_4 contain the remaining ones which appear in the multiset T^2 and let Ω_5 contain the remaining ones which do not. The partition $\{\Omega_i \mid 0 \leq i \leq 5\}$ forms a Schur ring over R, which leads to a 5-class association scheme. For a pseudo-planar function f, the set

$$D_f = \{x + 2\sqrt{f(x)} \mid x \in T\}$$

is also a $(2^n, 2^n, 2^n, 1)$-RDS in R with respect to Z (see [20]). Consequently, it is natural to ask whether an association scheme can also be obtained from D_f or not. In this section, we prove that any relative difference set D_f, which necessarily arises from a pseudo-planar function f, will produce an association scheme. In fact, the partition of R is obtained in a similar way. At first, we have four subsets

$$\mathcal{S}_0 = \{0\},\ \mathcal{S}_1 = D_f\backslash\{0\},\ \mathcal{S}_2 = \{-x \mid x \in \mathcal{S}_1\} = \mathcal{S}_1^{(-1)},\ \mathcal{S}_3 = Z\backslash\{0\}.$$

Furthermore, the remaining elements of R are divided into two classes. Let $\mathcal{S}_4$ contain the remaining ones which appear in the multiset D_f^2 and let $\mathcal{S}_5$ contain the remaining ones which do not.

Using the following lemma, it is straightforward to verify that $\{\mathcal{S}_i \mid 0 \leq i \leq 5\}$ indeed forms a partition of R.

Lemma 4.1 ([5, Theorem 1]). *Let $R = GR(4, n)$ and T be the Teichmüller system.*

1. *The multiset $TT^{(-1)}$ contains 0 with multiplicity 2^n, no other elements of Z, and the elements outside Z with multiplicity one.*
2. *The multiset T^2 contains the elements of Z with multiplicity one, and half of the elements outside Z with multiplicity two.*

Now we consider the dual partition of $\{\mathcal{S}_i \mid 0 \le i \le 5\}$ on the character group $\widehat{R}$. According to [20, Theorem 3], if f is pseudo-planar then $\chi(D_f)$ takes six values when χ ranges over $\widehat{R}$. More precisely,

$$\chi_a(D_f) = \begin{cases} 2^n & \text{for } a = 0, \\ 0 & \text{for } a \in Z\backslash\{0\}, \\ \pm 2^{(n-1)/2} \pm 2^{(n-1)/2}\mathbf{i} & \text{for } a \in R\backslash Z, \end{cases}$$

when n is odd and

$$\chi_a(D_f) = \begin{cases} 2^n & \text{for } a = 0, \\ 0 & \text{for } a \in Z\backslash\{0\}, \\ \pm 2^{n/2} or \pm 2^{n/2}\mathbf{i} & \text{for a } \in R\backslash Z, \end{cases}$$

when n is even. Furthermore, it is natural to investigate the frequencies of these six values when χ ranges over $\widehat{R}$. Similar to the case of almost perfect nonlinear functions, we introduce the definition of Fourier spectrum of a pseudo-planar function f as follows.

Definition 4.1 The Fourier spectrum of a pseudo-planar function f is defined to be the multiset

$$\{\chi(D_f) \mid \chi \in \widehat{R}\}.$$

As a consequence of Theorem 4.4 below, we can show that the Fourier spectrum is the same for every pseudo-planar function.

Note that $\chi(\mathcal{S}_1) = \chi(D_f) - 1$. There is a natural partition $\{\mathcal{E}_i \mid 0 \le i \le 5\}$ on the character group $\widehat{R}$, where χ_a and χ_b are in the same class if and only if $\chi_a(\mathcal{S}_1) = \chi_b(\mathcal{S}_1)$. The partition $\{\mathcal{E}_i \mid 0 \le i \le 5\}$ is given as follows:

$$\begin{aligned} \mathcal{E}_0 &= \{\chi_0\}, \\ \mathcal{E}_1 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1\} = \{\chi_a \mid a \in Z\backslash\{0\}\}, \\ \mathcal{E}_2 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 + 2^{(n-1)/2} + 2^{(n-1)/2}\mathbf{i}\}, \\ \mathcal{E}_3 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 + 2^{(n-1)/2} - 2^{(n-1)/2}\mathbf{i}\}, \\ \mathcal{E}_4 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 - 2^{(n-1)/2} + 2^{(n-1)/2}\mathbf{i}\}, \\ \mathcal{E}_5 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 - 2^{(n-1)/2} - 2^{(n-1)/2}\mathbf{i}\}, \end{aligned} \tag{7}$$

when n is odd and

$$\begin{aligned} \mathcal{E}_0 &= \{\chi_0\}, \\ \mathcal{E}_1 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1\} = \{\chi_a \mid a \in Z\backslash\{0\}\}, \\ \mathcal{E}_2 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 + 2^{n/2}\}, \\ \mathcal{E}_3 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 - 2^{n/2}\}, \\ \mathcal{E}_4 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 + 2^{n/2}\mathbf{i}\}, \\ \mathcal{E}_5 &= \{\chi \in \widehat{R} \mid \chi(\mathcal{S}_1) = -1 - 2^{n/2}\mathbf{i}\}, \end{aligned} \tag{8}$$

when n is even.

In the following we show that $(R, \{\mathcal{S}_i\}_{i=0}^5)$ is a Schur ring, whose dual is $(\widehat{R}, \{\mathcal{E}_i\}_{i=0}^5)$. We first use Lemma 4.2 and Lemma 4.3 to prove that $\mathcal{S}_4$ can be expressed as a linear combination of $\mathcal{S}_1^2, \mathcal{S}_2$, and $\mathcal{S}_3$. Then the values of $\chi(\mathcal{S}_4)$ and $\chi(\mathcal{S}_5)$ can be determined where χ ranges over $\widehat{R}$. Combining this with Bannai-Muzychuk criterion, the result follows.

Lemma 4.2 *Let $R = GR(4, n)$, and f be a pseudo-planar function over $\mathbb{F}_{2^n}$ which can be identified with a map from T to T. Let $D_f = \{x + 2\sqrt{f(x)} \mid x \in T\}$ and $\mathcal{S}_1 = D_f\backslash\{0\}$.*

1. *The multiset $\mathcal{S}_1\mathcal{S}_1^{(-1)}$ consists of* 0 *with multiplicity* 2^n-1 *and the elements of* $\mathcal{S}_4\cup\mathcal{S}_5$ *with multiplicity one.*
2. *The multiset $\mathcal{S}_1^2$ contains the elements of $\mathcal{S}_3$ with multiplicity one. In $\mathcal{S}_1^2$, the multiplicity of an element outside $\mathcal{S}_3$ is either zero or two.*

Proof 1. Since f is pseudo-planar, the set D_f is an RDS with $D_fD_f^{(-1)}=2^n\mathcal{S}_0+(R-Z)$. It is easy to verify that $\mathcal{S}_1\mathcal{S}_1^{(-1)}=(2^n-1)\mathcal{S}_0+(R-Z-\mathcal{S}_1-\mathcal{S}_2)=(2^n-1)\mathcal{S}_0+\mathcal{S}_4+\mathcal{S}_5$.

2. For any $x,y,z\in T^*$, suppose $x+2\sqrt{f(x)}+y+2\sqrt{f(y)}=2z$. Then $x+2\sqrt{f(x)}=y+2(\sqrt{f(y)}\oplus z\oplus y)$. By the unique representation (2), we must have $x=y=z$. Hence $\mathcal{S}_1^2$ contains the elements of $\mathcal{S}_3$ with multiplicity one. Suppose $\mathcal{S}_1^2=\mathcal{S}_3+2U_f$, where $U_f=\sum_{g\in R\setminus\mathcal{S}_3}d_gg$, it suffices to show that $d_g=0$ or 1. Since $\mathcal{S}_1^2=\mathcal{S}_3+2U_f$, applying the principal character, we have

$$\sum_{g\in R\setminus\mathcal{S}_3}d_g=(2^n-1)(2^{n-1}-1). \tag{9}$$

Now, we consider the coefficient of 0 in $\mathcal{S}_1^2(\mathcal{S}_1^{(-1)})^2$. On one hand, $\mathcal{S}_1^2(\mathcal{S}_1^{(-1)})^2=(\mathcal{S}_1\mathcal{S}_1^{(-1)})^2=((2^n-1)\mathcal{S}_0+\mathcal{S}_4+\mathcal{S}_5)^2=(2^n-1)^2\mathcal{S}_0+2(2^n-1)(\mathcal{S}_4+\mathcal{S}_5)+(\mathcal{S}_4+\mathcal{S}_5)^2$. Since $\mathcal{S}_4+\mathcal{S}_5=\mathcal{S}_4^{(-1)}+\mathcal{S}_5^{(-1)}$ and $|\mathcal{S}_4\cup\mathcal{S}_5|=(2^n-1)(2^n-2)$, we have $[(\mathcal{S}_4+\mathcal{S}_5)^2]_0=(2^n-1)(2^n-2)$. Consequently, $[\mathcal{S}_1^2(\mathcal{S}_1^{(-1)})^2]_0=(2^n-1)(2^{n+1}-3)$. On the other hand, $\mathcal{S}_1^2(\mathcal{S}_1^{(-1)})^2=(\mathcal{S}_3+2U_f)(\mathcal{S}_3+2U_f^{(-1)})=\mathcal{S}_3^2+2\mathcal{S}_3U_f+2\mathcal{S}_3U_f^{(-1)}+4U_fU_f^{(-1)}$. It is easy to check that $[\mathcal{S}_1^2(\mathcal{S}_1^{(-1)})^2]_0=2^n-1+4\sum_{g\in R\setminus\mathcal{S}_3}d_g^2$. Therefore, we have

$$\sum_{g\in R\setminus\mathcal{S}_3}d_g^2=(2^n-1)(2^{n-1}-1). \tag{10}$$

By Equations (9)-(10), we have

$$\sum_{g\in R\setminus\mathcal{S}_3}d_g=\sum_{g\in R\setminus\mathcal{S}_3}d_g^2,$$

which implies that $d_g=0$ or 1. □

Now we proceed to determine U_f mentioned in the proof of Lemma 4.2.

Lemma 4.3 *Let $R=GR(4,n)$ and f be a pseudo-planar function over $\mathbb{F}_{2^n}$. Let $\mathcal{S}_i$, $0\le i\le 5$ be defined as above. Then we have*

1. $\mathcal{S}_1^2=\mathcal{S}_3+2\mathcal{S}_4$ *when n is odd;*
2. $\mathcal{S}_1^2=\mathcal{S}_3+2\mathcal{S}_2+2\mathcal{S}_4$ *when n is even.*

Proof We only present the proof for Assertion 2, because a similar method can be applied to Assertion 1. The partition $\{\mathcal{E}_i\mid 0\le i\le 5\}$ is given in (8). Define $m_i=|\mathcal{E}_i|$ for $0\le i\le 5$, then $m_0=1$ and $m_1=2^n-1$. As a preparation, we first consider the relations between m_2, m_3, m_4 and m_5. A straightforward computation shows that $\sum_{a\in R}\chi_a(D_f)=2^{2n}$. On the other hand,

$$\begin{aligned}\sum_{a\in R}\chi_a(D_f)&=m_0\cdot 2^n+m_1\cdot 0+m_2\cdot 2^{n/2}+m_3\cdot(-2^{n/2})+m_4\cdot 2^{n/2}\mathbf{i}+m_5\cdot(-2^{n/2}\mathbf{i})\\&=2^n+2^{n/2}(m_2-m_3)+2^{n/2}(m_4-m_5)\mathbf{i}.\end{aligned}$$

Consequently, we have

$$m_2 - m_3 = 2^{3n/2} - 2^{n/2},$$
$$m_4 - m_5 = 0.$$

By Lemma 4.2, $\mathcal{S}_1^2 = \mathcal{S}_3 + 2U_f$. For any $x, y \in T$, if $x + 2\sqrt{f(x)} + y + 2\sqrt{f(y)} = 0$, then $x = y + 2(\sqrt{f(x)} \oplus \sqrt{f(y)} \oplus y)$. The latter equation implies $x = y = 0$. Hence, 0 is not an element of $\mathcal{S}_1^2$, i.e., $U_f \cap \mathcal{S}_0 = \emptyset$. By definition, we see that $\mathcal{S}_4 \subset U_f$ and $\mathcal{S}_5 \cap U_f = \emptyset$. It remains to determine the relationship between $\mathcal{S}_1$, $\mathcal{S}_2$ and U_f.

Firstly, we consider $\mathcal{S}_1$. By the inversion formula,

$$\begin{aligned}
[D_f^2 D_f^{(-1)}]_0 &= \frac{1}{|R|}\sum_{a\in R}\chi_a(D_f^2 D_f^{(-1)}) \\
&= \frac{1}{|R|}\sum_{a\in R}|\chi_a(D_f)|^2\chi_a(D_f) \\
&= \frac{1}{|R|}(2^{3n} + 2^{3n/2}(m_2 - m_3) + 2^{3n/2}(m_4 - m_5)\mathbf{i}) \\
&= 2^{n+1} - 1.
\end{aligned}$$

Note that

$$D_f^2 D_f^{(-1)} = \mathcal{S}_1^2\mathcal{S}_1^{(-1)} + 2\mathcal{S}_1\mathcal{S}_1^{(-1)} + \mathcal{S}_1^2 + 2\mathcal{S}_1 + \mathcal{S}_2 + \mathcal{S}_0,$$

$[\mathcal{S}_1\mathcal{S}_1^{(-1)}]_0 = 2^n - 1$ and $[\mathcal{S}_0]_0 = 1$. It follows that $[\mathcal{S}_1^2\mathcal{S}_1^{(-1)}]_0$=0. Hence, $\mathcal{S}_1^2$ contains no element of $\mathcal{S}_1$, namely, $\mathcal{S}_1 \cap U_f = \emptyset$.

Secondly, we consider $\mathcal{S}_2$. By the inversion formula,

$$\begin{aligned}
[D_f^3]_0 &= \frac{1}{|R|}\sum_{a\in R}\chi_a(D_f)^3 \\
&= \frac{1}{|R|}(2^{3n} + 2^{3n/2}(m_2 - m_3) - 2^{3n/2}(m_4 - m_5)\mathbf{i}) \\
&= 2^{n+1} - 1.
\end{aligned}$$

From

$$D_f^3 = (\mathcal{S}_0 + \mathcal{S}_1)^3 = \mathcal{S}_0 + 3\mathcal{S}_1 + 3\mathcal{S}_1^2 + \mathcal{S}_1^3,$$

$[\mathcal{S}_0]_0 = 1$, and $[\mathcal{S}_1]_0 = [\mathcal{S}_1^2]_0 = 0$, it follows that $[\mathcal{S}_1^2\mathcal{S}_2^{(-1)}]_0 = [\mathcal{S}_1^3]_0 = 2^{n+1} - 2$. By Lemma 4.2, $\mathcal{S}_1^2$ contains each element of $\mathcal{S}_2$ with multiplicity at most two. On the other hand, we have $[\mathcal{S}_1^2\mathcal{S}_2^{(-1)}]_0 = 2|\mathcal{S}_2|$. Hence, each element of $\mathcal{S}_2$ appears in $\mathcal{S}_1^2$ with multiplicity exactly two. Therefore, when n is even, we have $\mathcal{S}_1^2 = \mathcal{S}_3 + 2\mathcal{S}_2 + 2\mathcal{S}_4$. □

The partition $\{\mathcal{S}_i \mid 0 \le i \le 5\}$ of R induces a partition $\{\mathcal{R}_i \mid 0 \le i \le 5\}$ of $R \times R$, where

$$\mathcal{R}_i = \{(x, y) \in R \times R \mid x - y \in \mathcal{S}_i\} \quad (0 \le i \le 5).$$

Now we are ready to prove that $(R, \{\mathcal{R}_i\}_{i=0}^5)$ indeed forms an association scheme.

Theorem 4.4 *Let $R = GR(4, n)$ and $\mathcal{S}_i$, $0 \le i \le 5$ be defined as above. Then $(R, \{\mathcal{S}_i\}_{i=0}^5)$ is a Schur ring, whose dual is $(\widehat{R}, \{\mathcal{E}_i\}_{i=0}^5)$. If $n \ge 3$, then $(R, \{\mathcal{R}_i\}_{i=0}^5)$ forms a 5-class* *association scheme, whose first eigenmatrix is given as follows. When n is odd, suppose* $b = 2^{(n-1)/2}$*, we have*

$$P = \begin{bmatrix} 1 & 2b^2-1 & 2b^2-1 & 2b^2-1 & 2b^4-3b^2+1 & 2b^4-3b^2+1 \\ 1 & -1 & -1 & 2b^2-1 & -b^2+1 & -b^2+1 \\ 1 & -1+b+b\mathbf{i} & -1+b-b\mathbf{i} & -1 & (1-b)(1-b\mathbf{i}) & (1-b)(1+b\mathbf{i}) \\ 1 & -1+b-b\mathbf{i} & -1+b+b\mathbf{i} & -1 & (1-b)(1+b\mathbf{i}) & (1-b)(1-b\mathbf{i}) \\ 1 & -1-b+b\mathbf{i} & -1-b-b\mathbf{i} & -1 & (1+b)(1-b\mathbf{i}) & (1+b)(1+b\mathbf{i}) \\ 1 & -1-b-b\mathbf{i} & -1-b+b\mathbf{i} & -1 & (1+b)(1+b\mathbf{i}) & (1+b)(1-b\mathbf{i}) \end{bmatrix}. \tag{11}$$

When n is even, suppose $b = 2^{(n-2)/2}$*, we have*

$$P = \begin{bmatrix} 1 & 4b^2-1 & 4b^2-1 & 4b^2-1 & 8b^4-10b^2+2 & 8b^4-2b^2 \\ 1 & -1 & -1 & 4b^2-1 & -2b^2+2 & -2b^2 \\ 1 & 2b-1 & 2b-1 & -1 & 2b^2-4b+2 & -2b^2 \\ 1 & -2b-1 & -2b-1 & -1 & 2b^2+4b+2 & -2b^2 \\ 1 & -1+2b\mathbf{i} & -1-2b\mathbf{i} & -1 & -2b^2+2 & 2b^2 \\ 1 & -1-2b\mathbf{i} & -1+2b\mathbf{i} & -1 & -2b^2+2 & 2b^2 \end{bmatrix}. \tag{12}$$

The second eigenmatrix is listed in Appendix.

Proof According to the Bannai-Muzychuk criterion, it suffices to prove that $\chi_j(\mathcal{S}_i)$ is a constant for any $\chi_j \in \mathcal{E}_j$, where $0 \le i, j \le 5$. This is trivially true for any $0 \le j \le 5$ and $0 \le i \le 3$, which can be verified by direct computations. By Lemma 4.3, we can obtain $\chi_j(\mathcal{S}_4)$ for any $0 \le j \le 5$. Then we get the values of $\chi_j(\mathcal{S}_5)$. The information of $\chi_j(\mathcal{S}_4)$ and $\chi_j(\mathcal{S}_5)$ completes the proof. □

Remark 4.5 (1) When $n = 1$, we have $\mathcal{S}_4 = \mathcal{S}_5 = \emptyset$. Then $(R, \{\mathcal{R}_i\}_{i=0}^5)$ is a 3-class association scheme. When $n = 2$, we get $\mathcal{S}_4 = \emptyset$. Then $(R, \{\mathcal{R}_i\}_{i=0}^5)$ forms a 4-class association scheme, whose first eigenmatrix can be easily determined as a submatrix of (11) or (12).

(2) The 5-class association scheme investigated in [5] can be regarded as a special case of our construction where the pseudo-planar function $f = 0$.

Corollary 4.6 *Suppose f is a pseudo-planar function over $\mathbb{F}_{2^n}$. Then the Fourier spectrum $\{\chi(D_f) \mid \chi \in \widehat{R}\}$ is that listed in Tables 2 or 3.*

Proof Note that the frequency of each value can be obtained from the cardinality of the set $|\mathcal{E}_i|$. According to the second eigenmatrices listed in Appendix, the result now follows. □

5 Concluding remarks

In this paper, three new classes of pseudo-planar binomial functions are provided. In addition, we present a class of association schemes derived from pseudo-planar functions, which can be considered as a natural generalization of the one studied in [5].

Table 2 Fourier spectrum, n odd, $b = 2^{(n-1)/2}$

Value	Frequency
$2b^2$	1
0	$2b^2 - 1$
$b + b\mathbf{i}$	$\frac{b(2b^3+2b^2-b-1)}{2}$
$b - b\mathbf{i}$	$\frac{b(2b^3+2b^2-b-1)}{2}$
$-b + b\mathbf{i}$	$\frac{b(2b^3-2b^2-b+1)}{2}$
$-b - b\mathbf{i}$	$\frac{b(2b^3-2b^2-b+1)}{2}$

Table 3 Fourier spectrum, n even, $b = 2^{(n-2)/2}$

Value	Frequency
$4b^2$	1
0	$4b^2 - 1$
$2b$	$b(4b^3 + 4b^2 - b - 1)$
$-2b$	$b(4b^3 - 4b^2 - b + 1)$
$2b\mathbf{i}$	$b^2(4b^2 - 1)$
$-2b\mathbf{i}$	$b^2(4b^2 - 1)$

Let $D_1, D_2 \subset G$ be two $(2^n, 2^n, 2^n, 1)$ relative difference sets. They are *equivalent* if there exist some $\alpha \in \mathrm{Aut}(G)$ and $a \in G$ such that $\alpha(D_1) = D_2 + a$.

Suppose f is a function from $\mathbb{F}_{2^n}$ to itself. It is proved in [20] that D_f is a $(2^n, 2^n, 2^n, 1)$-RDS in $R = GR(4, n)$ with respect to Z if and only if f is pseudo-planar. So we say that two pseudo-planar functions f_1 and f_2 are *equivalent* if the relative difference sets D_{f_1} and D_{f_2} are equivalent. By Corollary 4.6, the p-ranks and Smith normal forms of the relative difference set D_f associated with pseudo-planar functions are all the same. Therefore some other techniques are to be developed to solve the equivalence problem. The equivalence problem of pseudo-planar functions will be investigated in a manuscript prepared by Yue Zhou.

The following are several open problems.

1. All pseudo-planar binomials constructed in this paper are of type
$$f(x) = ax^{2^i+2^j} + bx^{2^k+2^l},$$
where $i \neq j, k \neq l$, and $\{i, j\} \neq \{k, l\}$. For $n \leq 9$, an exhaustive computer search shows that these pseudo-planar binomials can only exist on the finite field of the form $\mathbb{F}_{2^n} = \mathbb{F}_{2^{3m}}$. Therefore, it is interesting to examine that whether these pseudo-planar binomials can only exist in $\mathbb{F}_{2^n}$ with $3|n$ or not.
2. The necessary and sufficient condition we provided in Proposition 3.2 is not easily handled. It is desirable if one can derive a simpler characterization.

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6 Appendix

When n is odd, the second eigenmatrix of the association scheme is

$$Q=\begin{bmatrix} 1 & 2b^2-1 & \frac{b}{2}\left(2b^3+2b^2-b-1\right) & \frac{b}{2}\left(2b^3+2b^2-b-1\right) & \frac{b}{2}\left(2b^3-2b^2-b+1\right) & \frac{b}{2}\left(2b^3-2b^2-b+1\right) \\ 1 & -1 & \frac{b}{2}\left(b^2-1-(b^2+b)\mathbf{i}\right) & \frac{b}{2}\left(b^2-1+(b^2+b)\mathbf{i}\right) & \frac{b}{2}\left(1-b^2-(b^2-b)\mathbf{i}\right) & \frac{b}{2}\left(1-b^2+(b^2-b)\mathbf{i}\right) \\ 1 & -1 & \frac{b}{2}\left(b^2-1+(b^2+b)\mathbf{i}\right) & \frac{b}{2}\left(b^2-1-(b^2+b)\mathbf{i}\right) & \frac{b}{2}\left(1-b^2+(b^2-b)\mathbf{i}\right) & \frac{b}{2}\left(1-b^2-(b^2-b)\mathbf{i}\right) \\ 1 & 2b^2-1 & -\frac{b}{2}(1+b) & -\frac{b}{2}(1+b) & \frac{b}{2}(1-b) & \frac{b}{2}(1-b) \\ 1 & -1 & -\frac{b}{2}(1+b\mathbf{i}) & \frac{b}{2}(-1+b\mathbf{i}) & \frac{b}{2}(1+b\mathbf{i}) & \frac{b}{2}(1-b\mathbf{i}) \\ 1 & -1 & \frac{b}{2}(-1+b\mathbf{i}) & -\frac{b}{2}(1+b\mathbf{i}) & \frac{b}{2}(1-b\mathbf{i}) & \frac{b\left(b^2+1\right)}{2(1-b\mathbf{i})} \end{bmatrix}.$$

When n is even, the second eigenmatrix of the association scheme is

$$Q=\begin{bmatrix} 1 & 4b^2-1 & b\left(4b^3-b+4b^2-1\right) & b\left(4b^3-4b^2-b+1\right) & b^2\left(4b^2-1\right) & b^2\left(4b^2-1\right) \\ 1 & -1 & b\left(b+2b^2-1\right) & -\left(2b^2-b-1\right)b & -b^2(1+2b\mathbf{i}) & b^2(-1+2b\mathbf{i}) \\ 1 & -1 & b\left(b+2b^2-1\right) & -\left(2b^2-b-1\right)b & b^2(-1+2b\mathbf{i}) & -b^2(1+2b\mathbf{i}) \\ 1 & 4b^2-1 & -b(1+b) & -b(-1+b) & -b^2 & -b^2 \\ 1 & -1 & b(-1+b) & b(1+b) & -b^2 & -b^2 \\ 1 & -1 & -b(1+b) & -b(-1+b) & b^2 & b^2 \end{bmatrix}.$$

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