Bent partitions and Maiorana-McFarland association schemes

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Outline

- Bent functions and bent partitions
- Generalized semifield spreads and generalized PS_{ap} functions
- Association schemes from vectorial dual-bent functions
- Maiorana-McFarland association schemes

Definition Let $F : \mathbb{V}_n^{(p)} \to \mathbb{V}_m^{(p)}$ be a function. The Walsh transform of F is the complex valued function

$$\mathcal{W}_F(a,b) = \sum_{x \in \mathbb{V}_n^{(p)}} \epsilon_p^{\langle a, F(x)\rangle_m - \langle b, x\rangle_n}, \quad \epsilon_p = e^{2\pi i/p},$$

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where $\langle , \rangle_k$ denotes a non-degenerate inner product in $\mathbb{V}_k^{(p)}$.

A function $F : \mathbb{V}_n^{(p)} \to \mathbb{V}_m^{(p)}$ is called a bent function if $|\mathcal{W}_F(a,b)| = p^{n/2}$ for all nonzero $a \in \mathbb{V}_m^{(p)}$ and $b \in \mathbb{V}_n^{(p)}$.

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If $m = 1$, then F is also called a p-ary bent function (Boolean if $p = 2$). The Walsh transform of a p-ary function $F : \mathbb{V}_n^{(p)} \to \mathbb{F}_p$ is of the form

$$\mathcal{W}_F(1,b) = \mathcal{W}_F(b) = \sum_{x \in \mathbb{V}_n^{(p)}} \epsilon_p^{F(x) - \langle b, x\rangle_n}.$$

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If $m > 1$, then F is also called a vectorial bent function. The p-ary functions $F_a(x) = < a, F(x) >_m$ for nonzero $a \in \mathbb{V}_m^{(p)}$ are called the component functions of F, and form a vector space of bent functions of dimension m.

Regularity Boolean bent function $f : \mathbb{V}_n^{(2)} \to \mathbb{F}_2$: $\mathcal{W}_f(b) = 2^{n/2}(-1)^{f^*(b)}$, f^* is a Boolean bent function.

Walsh coefficient $\mathcal{W}_f(b)$ for a p-ary bent function $f : \mathbb{V}_n^{(p)} \to \mathbb{F}_p$, at $b \in \mathbb{V}_n^{(p)}$:

$$\mathcal{W}_f(b) = \begin{cases} \pm\epsilon_p^{f^*(b)} p^{n/2} & : \quad p^n \equiv 1 \bmod 4; \\ \pm i\epsilon_p^{f^*(b)} p^{n/2} & : \quad p^n \equiv 3 \bmod 4, \end{cases}$$

$f^* : \mathbb{V}_n^{(p)} \to \mathbb{F}_p$, called the dual of f.
A bent function $f : \mathbb{V}_n^{(p)} \to \mathbb{F}_p$ is called weakly regular if, $\mathcal{W}_f(b) = \zeta\ \epsilon_p^{f^*(b)} p^{n/2}$ for all $b \in \mathbb{V}_n^{(p)}$, $\zeta \in \{\pm 1, \pm i\}$ fixed,
regular $\zeta = 1$,
otherwise f is called non-weakly regular.

The dual of a weakly regular bent function is also bent.

Example (Construction of bent functions with a complete spread)

Let $n = 2m$. Consider the partition of $\mathbb{V}_n^{(p)}$ via a spread, $\Omega = \{U_0, U_1^*, \ldots, U_{p^m}^*\}$ of $\mathbb{V}_n^{(p)}$, where

- $U_i \leq \mathbb{V}_n^{(p)}$ and $\dim(U_i) = m$ for all $0 \leq i \leq p^m$,
- $U_i \cap U_j = \{0\}$ for all $0 \leq i < j \leq p^m$,
- $U_i^* = U_i \setminus \{0\}$, for all $1 \leq i \leq p^m$, (i.e., $\{U_0, U_1, \ldots, U_{p^m}\}$ is a complete spread of $\mathbb{V}_n^{(p)}$).

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One can obtain bent functions from $\mathbb{V}_n^{(p)}$ to $\mathbb{F}_p$ as follows.

I) For every $c \in \mathbb{F}_p$, the elements of exactly p^{m-1} of U_j^*, $1 \leq j \leq p^m$ are mapped to c.

II) The elements of U_0 are mapped to a fixed $c_0 \in \mathbb{F}_p$.

Desarguesian spread

Let $n = 2m$ and $\mathbb{V}_n^{(p)} = \mathbb{F}_{p^m} \times \mathbb{F}_{p^m}$. Consider

- $U_s = \{(x, sx) : x \in \mathbb{F}_{p^m}\}$ for each $s \in \mathbb{F}_{p^m}$,
- $U = \{(0, y) : y \in \mathbb{F}_{p^m}\}$.

Then $\{U_0, U_s : s \in \mathbb{F}_{p^m}\}$ is the Desarguesian spread.

The class of bent functions obtained from the Desarguesian spread is called the class of PS_{ap} bent functions. The functions in the class of PS_{ap} bent functions are explicitly of the form

$$F(x, y) = B(yx^{p^m-2}),$$

where $B : \mathbb{F}_{p^m} \to \mathbb{F}_p$ is any balanced function.

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Semifield spread: Finite field multiplication $\longrightarrow$ semifield operation $\circ$.

Definition (Anbar, Meidl, 2022) A partition $\Omega = \{U, A_1, \ldots, A_K\}$ of $\mathbb{V}_n^{(p)}$ into an $n/2$-dimensional subspace U and sets $A_1, \ldots, A_K$, is called a bent partition of $\mathbb{V}_n^{(p)}$ of depth K, if every function with the following properties is bent.

I) Every $c \in \mathbb{F}_p$ has exactly K/p of the sets $A_1, \ldots, A_K$ in its preimage set $f^{-1}(c) = \{x \in \mathbb{V}_n^{(p)} : f(x) = c\}$,

II) $f(x) = c_0$ for all $x \in U$ and some fixed $c_0 \in \mathbb{F}_p$.

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Examples: Generalized semifield spreads

Definition Let $\circ$ be a binary operation on an m dimensional vector space $\mathbb{V}_m^{(p)}$, without loss of generality $\mathbb{F}_{p^m}$, satisfying

I) $x \circ y = 0 \Rightarrow x = 0$ or $y = 0$,

II) $(x + y) \circ s = (x \circ s) + (y \circ s)$ and $s \circ (x + y) = (s \circ x) + (s \circ y)$,

for all $x, y, s \in \mathbb{F}_{p^m}$. Then $P = (\mathbb{F}_{p^m}, +, \circ)$ is called a presemifield.

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A presemifield, for which there is an element $e \neq 0$ such that $e \circ x = x \circ e = x$ for all $x \in \mathbb{F}_{p^m}$, is a semifield.

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Given a (pre)semifield $P = (\mathbb{F}_{p^m}, +, \circ)$, consider the (pre)semifield $P^d = (\mathbb{F}_{p^m}, +, \star)$ obtained by defining $x \star y$ with the equation

$$\mathrm{Tr}_1^m(x(b \star y)) = \mathrm{Tr}_1^m(b(x \circ y)) \text{ for all } b, x, y \in \mathbb{F}_{p^m}.$$

Then P^d is called the dual of P.

Generalized semifield spread

Let $P = (\mathbb{F}_{p^m}, +, \circ)$ be a (pre)semifield, $m,\ k, e \in \mathbb{Z}^+$ such that $k \mid m$, $e = p^k + p - 1$, $\gcd(p^m - 1, e) = 1$. Consider the following partition of $\mathbb{F}_{p^m} \times \mathbb{F}_{p^m}$.

$$\Omega = \{U, \mathcal{A}(\gamma) : \gamma \in \mathbb{F}_{p^k}\}$$

$$\mathcal{A}(\gamma) = \bigcup_{s \in \mathbb{F}_{p^m} : \mathrm{Tr}_k^m(s) = \gamma} U_s^* \qquad \text{where} \quad U_s = \{(x, s \circ x^e) : x \in \mathbb{F}_{p^m}\},$$

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Theorem (Anbar, K., Meidl, 2023) Suppose that $P = (\mathbb{F}_{p^m}, +, \circ)$ is a (pre)semifield such that the dual $P^d = (\mathbb{F}_{p^m}, +, \star)$ satisfies

$$x \star (cy) = c(x \star y) \quad \text{for all } x, y \in \mathbb{F}_{p^m}, c \in \mathbb{F}_{p^k},$$

(i.e., P^d is right $\mathbb{F}_{p^k}$-linear). Then Ω is a bent partition of $\mathbb{F}_{p^m} \times \mathbb{F}_{p^m}$.

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Remark. More general, $e \equiv p^l \bmod (p^k - 1)$.

Recall The class of bent functions obtained from the Desarguesian spread is called the class of PS_{ap} bent functions. The functions in the class of PS_{ap} bent functions are explicitly of the form

$$F(x,y) = B(yx^{p^m-2}),$$

where $B : \mathbb{F}_{p^m} \to \mathbb{F}_p$ is any balanced function.

The bent functions from a generalized Desarguesian spread can be explicitly written as

$$F(x,y) = B(\mathrm{Tr}_k^m(yx^{-e})),$$

where $k \mid m, e \equiv p^l \bmod (p^k-1), \gcd(p^m-1, e) = 1$, and $B : \mathbb{F}_{p^k} \to \mathbb{F}_p$ is a balanced function. We call a function of the form F a generalized PS_{ap} function.

Theorem (Anbar, K., Meidl, Özbudak, 2024) Let k divide m, $\gcd(e, p^m - 1) = 1$ and $e \equiv p^l \bmod (p^k - 1)$.

(i) In general, two bent partitions (generalized Desarguesian spreads) obtained with different choices of e are not equivalent.

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(ii) For some given m and k, varying e, one can generate generalized PS_{ap} bent functions of various algebraic degree.

Recall. The algebraic degree of a (partial) spread bent function from $\mathbb{V}_{2m}^{(p)}$ to $\mathbb{F}_p$ is $(p-1)m$ (Dillon 1976, Anbar, Meidl 2022).

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- *Explicitly we can construct such generalized PS_{ap} bent functions with algebraic degree $s(p-1)$ for $s = k, k+1, \ldots, m-1$.*

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Remark. Experimental results (Magma) show that the generalized PS_{ap} class contains bent functions with many more algebraic degrees.

Vectorial dual-bent function

Definition (Çeşmelioğlu, Meidl, Pott, 2018) Let $F : \mathbb{V}_n^{(p)} \to \mathbb{V}_m^{(p)}$ be a vectorial bent function, i.e., the component functions of F form an m-dimensional vector space of bent functions of dimension m. Then F is called vectorial dual-bent if the set

$$\{(F_a)^* : a \in \mathbb{V}_m^{(p)} \setminus \{0\}\} = \{\langle a, F\rangle_m^* : a \in \mathbb{V}_m^{(p)} \setminus \{0\}\}$$

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The set $\{(F_a)^* : a \in \mathbb{V}_m^{(p)} \setminus \{0\}\}$ is then the set of the component functions of some other vectorial bent function F^* from $\mathbb{V}_n^{(p)}$ to $\mathbb{V}_m^{(p)}$, called a vectorial dual of F, and there exists a permutation σ of $\mathbb{V}_k^{(p)}$ with $\sigma(0) = 0$, such that

$$(F_\alpha)^* = F^*_{\sigma(\alpha)}, \quad \alpha \in \mathbb{F}_{p^k} \setminus \{0\}.$$

Theorem (Anbar, Meidl, 2022) Let $\{U, A_1, \ldots, A_K\}$ be a bent partition of $\mathbb{V}_n^{(p)}$, and suppose that $K = p^k$. Then every function $F : \mathbb{V}_n^{(p)} \to \mathbb{V}_k^{(p)}$ such that every element $c \in \mathbb{V}_k^{(p)}$ has the elements of exactly one of the sets A_j, $1 \leq j \leq p^k$, in its preimage, and U is mapped to some element c_0, is a vectorial bent function.

Proposition (Wang, Fu, Wei, 2023) For every generalized semifield spread Ω there exists a vectorial bent function F obtained from Ω, which is vectorial dual-bent with identity permutation.

$$(F_\alpha)^* = F^*_{\sigma(\alpha)}, \quad \alpha \in \mathbb{F}_{p^k} \setminus \{0\}.$$

Definition

• A d-class association scheme is a set of binary relations $R_0, R_1, \ldots, R_d$ on a set V satisfying the following properties:

I) $R_0 = \{(x,x) : x \in V\}$ is the identity relation on V.

II) $\bigcup_{i=0}^{d} R_i = V \times V$, $R_i \cap R_j = \emptyset$ if $i \neq j$, i.e., the relations R_i, $0 \leq i \leq d$, form a partition of $V \times V$.

III) For every $0 \leq i \leq d$, $R_i^t = R_{i'}$ for some $0 \leq i' \leq d$, where $R_i^t = \{(x,y) : (y,x) \in R_i\}$.

IV) For every $h, i, j \in \{0, 1, \ldots, d\}$ there exists a constant ρ_{ij}^h, called an intersection number, such that for every $(x,y) \in R_h$, the number of z such that $(x,z) \in R_i$ and $(z,y) \in R_j$ equals ρ_{ij}^h.

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- A fusion of an association scheme $\{R_0, R_1, \ldots, R_d\}$ on V is a partition $\{S_0, S_1, \ldots, S_e\}$ of $V \times V$, such that $S_0 = R_0$, and S_i, $1 \leq i \leq e$, is the union of some of the relations R_j.

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IV) For every $h, i, j \in \{0, 1, \ldots, d\}$ there exists a constant ρ_{ij}^h, called an intersection number, such that for every $(x,y) \in R_h$, the number of z such that $(x,z) \in R_i$ and $(z,y) \in R_j$ equals ρ_{ij}^h.

- A fusion of an association scheme $\{R_0, R_1, \ldots, R_d\}$ on V is a partition $\{S_0, S_1, \ldots, S_e\}$ of $V \times V$, such that $S_0 = R_0$, and S_i, $1 \leq i \leq e$, is the union of some of the relations R_j.
- An association scheme is called amorphic if any of its fusions is again an association scheme.

Vectorial dual-bent functions and association schemes

Theorem (Anbar, K., Meidl, Özbudak, 2023, Wang et al., 2024) Let $F : \mathbb{V}_n^{(p)} \to \mathbb{V}_m^{(p)}$ be a vectorial dual-bent function, $F(0) = 0$, $F(x) = F(-x)$. Suppose that all components of F are either regular or all are weakly regular but not regular. For the preimage sets $D_{F,\alpha} = \{x \in \mathbb{V}_n^{(p)} \setminus \{0\} \ : \ F(x) = \alpha\}$ consider the binary relations R_α with $(x, y) \in R_\alpha$ iff $x - y \in D_{F,\alpha}$.

(i) Then the set of relations $\{id, R_\alpha \ : \ \alpha \in \mathbb{V}_m^{(p)}\}$ forms a p^m-class association scheme on $\mathbb{V}_n^{(p)}$, except for the case that all components of F are weakly regular but not regular and $m = \frac{n}{2}$, in which case we have a $(p^m - 1)$-class association scheme (p must then be 3).

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Corollary. Every generalized semifield spread (bent partition of depth p^k) yields an amorphic p^k-class association scheme.

Examples (in the Maiorana-McFarland class)

Let e, d be integers such that $\gcd(e, p^m - 1) = 1$ and $ed \equiv 1 \bmod (p^m - 1)$.

- $F(x, y) = yx^{-e}$, $\gcd(e, p^m - 1) = 1$, is vectorial dual-bent from $\mathbb{F}_{p^m} \times \mathbb{F}_{p^m}$ to $\mathbb{F}_{p^m}$, with vectorial dual $F(x, y) = -xy^{-d}$.

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- For a divisor k of m, the projection $F_1(x, y) = \mathrm{Tr}_k^m(yx^{-e})$ is vectorial dual-bent. The association scheme for F_1 is a fusion scheme of the association scheme of F, which is amorphic if $e \equiv p^l \bmod (p^k - 1)$.

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- Let $P = (\mathbb{F}_{p^m}, +, \circ)$ be a (pre)semifield, and $a(x, y) : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \to \mathbb{F}_{p^m}$ be defined by

$$a(x, y) \circ x^e = y \quad \text{if} \quad x \neq 0 \quad \text{and} \quad a(x, y) = 0 \quad \text{if} \quad x = 0.$$

  If for a divisor k of m the dual presemifield P^{d} is right $\mathbb{F}_{p^k}$-linear, then $F : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \to \mathbb{F}_{p^k}$ given by $F(x, y) = \mathrm{Tr}_k^m(a(x, y))$ is a vectorial dual-bent function. (Anbar, K., Meidl, Özbudak 2024)

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Consequence. From a right $\mathbb{F}_{p^k}$-linear semifield $P = (\mathbb{F}_{p^m}, +, \circ)$ we get a vectorial dual-bent function, association scheme. With an exponent $e \equiv p^l \bmod (p^k - 1)$, the association scheme is amorphic, bent partition.

Fusions of MMF association schemes

Theorem (Anbar, K., Meidl, Özbudak 2024) Let $F : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \to \mathbb{F}_{p^k}$ be a (Maiorana-McFarland) vectorial dual-bent function as above, i.e., $F(x, y) = yx^{-e}$ respectively $F(x, y) = \mathrm{Tr}_k^m(a(x, y))$. Let $\mathbb{F}_{p^s}$ be any subfield of $\mathbb{F}_{p^m}$ respectively $\mathbb{F}_{p^k}$.

(i) The projection $F^{\gamma,s}$ of F to any coset $\gamma\mathbb{F}_{p^s}$ of $\mathbb{F}_{p^s}$ is a vectorial dual-bent function. The preimage set partition of $F^{\gamma,s}$ induces a fusion scheme of the association scheme obtained from F. For different cosets of $\mathbb{F}_{p^s}$, we obtain different fusion schemes.

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(ii) If $e \equiv p^j \bmod (p^s - 1)$, then the preimage set partition of $F^{\gamma,s}$ is a bent partition of $\mathbb{F}_{p^m} \times \mathbb{F}_{p^m}$, the corresponding fusion scheme is amorphic.

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