A NOTE ON SEMI-BENT BOOLEAN FUNCTIONS

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Abstract. We show how to construct semi-bent Boolean functions from $\mathcal{PS}_{ap}$-like bent functions. We derive infinite classes of semi-bent functions in even dimension having multiple trace terms.

Keywords. Boolean function, Bent functions, Maximum nonlinearity, Semi-bent function, Walsh-Hadamard transformation, Partial Spread class.

1. Introduction

A number of research works in symmetric cryptography are devoted to problems of resistance of various ciphering algorithms to the fast correlation attacks (on stream ciphers) and the linear cryptanalysis (on block ciphers) and to the analysis of various classes of approximating functions and constructions of functions with the best resistance to such approximations. Some general classes of Boolean functions play a central role with this respect: the class of bent functions [33], i.e., of Boolean functions of an even number of variables that have the maximum possible Hamming distance from the set of all affine functions (see for instance [5]), its subclasses of homogeneous bent functions [32], hyper-bent functions [34], and generalizations of the notion: semi-bent functions [9], Z-bent functions [12], negabent functions [31], etc.

In this paper we investigate constructions of the so called *semi-bent functions*. The term of semi-bent function has been introduced by Chee, Lee and Kim at Asiacrypt' 94. These functions have been previously investigated under the name of 3-valued almost optimal Boolean functions in [2]. Also, they are particular cases of the so-called plateaued functions [35]. Semi-bent functions are studied in cryptography because, besides having low Hadamard transform which provides protection against fast correlation attacks [25] and linear cryptanalysis [23], they can possess desirable properties in addition to the propagation criterion and low additive autocorrelation, such as resiliency and high algebraic degree.

The paper is organized as follows. In section 2, we fix our main notation and recall the necessary background. Next, in section 3, given a spread of $\mathbb{F}_{2^n}$, we consider two particular kinds of bent functions defined over $\mathbb{F}_{2^n}$ whose restrictions to the elements of the spread are constant or linear. We show in Theorem 1 that the sum of two bent functions of each kind is semi-bent and we prove that all the semi-bent functions whose restrictions to the elements of the spread are affine equal such sums. We also provide a more general statement than Theorem 1 for Partial spreads (Theorem 2). Section 4 is devoted to constructions of semi-bent functions.

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2. Notation and preliminaries

For any set E, we will denote $E \setminus \{0\}$ by $E^\star$ and the cardinality of E by $\#E$.

- *Boolean functions and polynomial forms*:

Let n be a positive integer. A Boolean function f on $\mathbb{F}_{2^n}$ is an $\mathbb{F}_2$-valued function over the Galois field $\mathbb{F}_{2^n}$ of order 2^n (or over the vector space $\mathbb{F}_2^n$ but in this paper we shall always endow this vector space with the structure of field, thanks to the choice of a basis of $\mathbb{F}_{2^n}$ over $\mathbb{F}_2$). The *weight* of f, denoted by $\mathrm{wt}(f)$, is the *Hamming weight* of the image vector of f, that is, the cardinality of its support $Supp(f) := \{x \in \mathbb{F}_{2^n} \mid f(x) = 1\}$.
For any positive integer k, and for any r dividing k, the trace function from $\mathbb{F}_{2^k}$ to $\mathbb{F}_{2^r}$, denoted by Tr_r^k, is the mapping defined as: $\forall x \in \mathbb{F}_{2^k}, \quad Tr_r^k(x) := \sum_{i=0}^{\frac{k}{r}-1} x^{2^{ir}}$.
In particular, the *absolute trace* over $\mathbb{F}_2$ is the function $Tr_1^n(x) = \sum_{i=0}^{n-1} x^{2^i}$.

Recall that, for every integer r dividing k, the trace function Tr_r^k satisfies the transitivity property, that is, $Tr_1^k = Tr_1^r \circ Tr_r^k$.
Every non-zero Boolean function f defined over $\mathbb{F}_{2^n}$ has a (unique) trace expansion of the form:

$$\forall x \in \mathbb{F}_{2^n}, \quad f(x) = \sum_{j \in \Gamma_n} Tr_1^{o(j)}(a_j x^j) + \epsilon(1 + x^{2^n-1})$$

called its polynomial form, where Γ_n is the set of integers obtained by choosing one element in each cyclotomic coset of 2 modulo $2^n - 1$, $o(j)$ is the size of the cyclotomic coset of 2 modulo $2^n - 1$ containing j, $a_j \in \mathbb{F}_{2^{o(j)}}$ and, $\epsilon = \mathrm{wt}(f)$ modulo 2. The algebraic degree of f is equal to the maximum 2-weight of an exponent j for which $a_j \neq 0$ if $\epsilon = 0$ and to n if $\epsilon = 1$.

- *Niho power functions:*

Let $n = 2m$ be an even integer. Recall that a positive integer d (always understood modulo $2^n - 1$) is said to be a *Niho exponent*, and x^d is a *Niho power function*, if the restriction of x^d to $\mathbb{F}_{2^m}$ is linear or in other words $d \equiv 2^j \pmod{2^m - 1}$ for some $j < n$. As we consider $Tr_1^n(x^d)$, without loss of generality, we can assume that d is in the normalized form, with $j = 0$, and then we have a unique representation $d = (2^m - 1)s + 1$ with $2 \leq s \leq 2^m$.

- *Walsh Hadamard transform*:

Let f be a Boolean function on $\mathbb{F}_{2^n}$. Its *"sign" function* is the integer-valued function $\chi(f) := (-1)^f$. The Walsh Hadamard transform of f is the discrete Fourier transform of χ_f, whose value at $\omega \in \mathbb{F}_{2^n}$ is defined as follows:

$$\forall \omega \in \mathbb{F}_{2^n}, \quad \widehat{\chi_f}(\omega) = \sum_{x \in \mathbb{F}_{2^n}} (-1)^{f(x) + Tr_1^n(\omega x)}.$$

Recall the well-known Parseval's relation

$$\sum_{\omega \in \mathbb{F}_{2^n}} \widehat{\chi_f}^2(\omega) = 2^{2n}.$$

and also this inverse formula

$$\sum_{\omega\in\mathbb{F}_{2^n}} \widehat{\chi_f}(\omega) = 2^n(-1)^{f(0)}.$$

It is easy to see that not all values of the values of the Walsh transform have the same sign. This comes from the fact that

$$\left(\sum_{\omega\in\mathbb{F}_{2^n}} \widehat{\chi_f}(\omega)\right)^2 = \sum_{\omega\in\mathbb{F}_{2^n}} \widehat{\chi_f}^2(\omega)$$

which implies that it is impossible to have $\widehat{\chi_f}(\omega) \geq 0$ for all ω as well $\widehat{\chi_f}(\omega) \leq 0$ for all ω, unless f is affine.

- *Bent, semi-bent and hyper-bent functions*:
  Bent functions [33] can be defined as follows:

Definition 1. A Boolean function $f : \mathbb{F}_{2^n} \to \mathbb{F}_2$ (n even) is said to be bent if $\widehat{\chi_f}(\omega) = \pm 2^{\frac{n}{2}}$, for all $\omega \in \mathbb{F}_{2^n}$.

Semi-bent functions [9, 10] can be defined as follows, for n even and for n odd:

Definition 2. Let n be an even integer. A Boolean function $f : \mathbb{F}_{2^n} \to \mathbb{F}_2$ is said to be semi-bent if if $\widehat{\chi_f}(\omega) \in \{0, \pm 2^{\frac{n+2}{2}}\}$, for all $\omega \in \mathbb{F}_{2^n}$.

It is well Known (see for instance [5]) that the algebraic degree of a semi-bent Boolean function defined on $\mathbb{F}_{2^n}$ is at most $\frac{n}{2}$.

Definition 3. Let n be an odd integer. A Boolean function $f : \mathbb{F}_{2^n} \to \mathbb{F}_2$ is said to be semi-bent if if $\widehat{\chi_f}(\omega) \in \{0, \pm 2^{\frac{n+1}{2}}\}$, for all $\omega \in \mathbb{F}_{2^n}$.

Hyper-bent functions [34] have properties still stronger than bent functions. More precisely, they can be defined as follows:

Definition 4. A Boolean function $f : \mathbb{F}_{2^n} \to \mathbb{F}_2$ (n even) is said to be hyper-bent if the function $x \mapsto f(x^i)$ is bent, for every integer i co-prime with $2^n - 1$.

- *The Dillon Partial Spread classes*:

The Partial Spread class $\mathcal{PS}$, introduced in [11] by Dillon, is the set of all the sums (modulo 2) of the indicators of $2^{\frac{n}{2}-1}$ or $2^{\frac{n}{2}-1}+1$ disjoint $\frac{n}{2}$-dimensional subspaces of $\mathbb{F}_{2^n}$ (disjoint meaning that any two of these spaces intersect in 0 only, and therefore that their sum is direct and equals $\mathbb{F}_{2^n}$). Dillon denotes by $\mathcal{PS}^-$ (resp. $\mathcal{PS}^+$) the class of those bent functions for which the number of $\frac{n}{2}$-dimensional subspaces is $2^{\frac{n}{2}-1}$ (resp. $2^{\frac{n}{2}-1}+1$).

Dillon exhibits a subclass of $\mathcal{PS}^-$, denoted by $\mathcal{PS}_{ap}$, whose elements are defined in an explicit form:

Definition 5. Let $n = 2m$. The Partial Spread class $\mathcal{PS}_{ap}$ consists of all functions f defined over $\mathbb{F}_{2^n}$ as follows: let g be a balanced Boolean function over $\mathbb{F}_{2^m}$ (ie. $wt(g) = 2^{m-1}$) such that $g(0) = 0$ (in fact this last condition is not necessary for f to be bent). Define a Boolean function f from $\mathbb{F}_{2^m} \times \mathbb{F}_{2^m}$ to $\mathbb{F}_2$ as $f(x, y) = g(\frac{x}{y})$ (i.e $g(xy^{2^m-2})$) with $\frac{x}{y} = 0$ if $y = 0$.

All the bent functions from the PS_{ap} class defined by Dillon [11] are hyper-bent. They are the functions or the complements of the functions defined over $\mathbb{F}_{2^n}$ and whose supports have the form $\bigcup_{u\in S} u\mathbb{F}_{2^m}^{\star}$ where U is the set $\{u \in \mathbb{F}_{2^n} \mid u^{2^m+1} = 1\}$ and S is a subset of U of size 2^{m-1}.

In the whole paper $n = 2m$ is an (even) integer.

3. Characterizations of semi-bent functions

Recall [11] that a collection $\{E_i,\, i = 1, \ldots, 2^m + 1\}$ of vector spaces of dimension m such that:

(1) $E_i \cap E_j = \{0\}$ for every i and j,

(2) $\bigcup_{i=1}^{2^m+1} E_i = \mathbb{F}_{2^n}$.

is called a *spread*.

Conjecture 1. We conjecture that, for every spread $\{E_i,\, i = 1, \ldots, 2^m + 1\}$, there exists a bent Boolean function h defined over $\mathbb{F}_{2^n}$ such that, for every i, the restriction of h to E_i is linear.

In the next theorem, we characterize when a function whose restriction to every E_i^* is affine is semi-bent:

Theorem 1. *Let $m \geq 2$ and $n = 2m$. Let $\{E_i,\, i = 1, \ldots, 2^m + 1\}$ be a spread in $\mathbb{F}_{2^n}$ and h a Boolean function whose restriction to every E_i is linear. Let S be any subset of $\{1, \ldots, 2^m + 1\}$ and $g = \sum_{i\in S} 1_{E_i} \pmod 2$ where 1_{E_i} is the indicator of E_i. Then $g + h$ is semi-bent if and only if g and h are bent.*

Note that g is then in the Partial Spread class PS and h is in a class generalizing the class that Dillon denotes by H in [11].

We can modify the hypothesis of Theorem 1 by assuming that we have only a partial spread. We need then to add a condition on the E_i's, and we have only a sufficient condition (not a necessary and sufficient one) for $g + h$ being semi-bent:

Theorem 2. *Let g be a bent function in the PS class, equal to the sum modulo 2 of the indicators of $l := 2^{m-1}$ or $2^{m-1} + 1$ pairwise "disjoint" vector paces E_i having dimension m, and h a bent function which is linear on each E_i. Assume additionally that for every $c \in \mathbb{F}_{2^n}$ there exist at most 2 indices i such that $\forall e \in E_i$, $h(e) = Tr_1^n(ce)$. Then $g + h$ is semi-bent.*

4. Constructions of semi-bent functions

4.1. **Constructions in bivariate form.** Let $\mathbb{F}_{2^n}$ be identified with $\mathbb{F}_{2^m} \times \mathbb{F}_{2^m}$ thanks to the choice of an orthonormal basis ($\mathbb{F}_{2^n}$ being identified with $\mathbb{F}_{2^m} \times \mathbb{F}_{2^m}$ thanks to the choice of a basis $(1, w)$ of $\mathbb{F}_{2^n}$ over $\mathbb{F}_{2^m}$). We consider the vector spaces $E_a = \{(x, ax);\, x \in \mathbb{F}_{2^m}\}$ where $a \in \mathbb{F}_{2^m}$ and $E_\infty = \{(0, y);\, y \in \mathbb{F}_{2^m}\} = \{0\} \times \mathbb{F}_{2^m}$. The bivariate version of the spread $\{u\mathbb{F}_{2^m}\,;\, u \in U\}$ is the spread $\{E_a\,;\, a \in \mathbb{F}_{2^m}\} \cup \{E_\infty\}$. It can be directly checked that the E_a's and E' are indeed vector spaces of dimension m, and we have $E_a \cap E_b = \{0\}$ for every pair (a, b) such that $a \neq b$ and $E_\infty \cap E_a = \{0\}$ for every $a \in \mathbb{F}_{2^m}$. Note that any function g in the PS_{ap} class can be viewed as the indicator of 2^{m-1} or $2^{m-1} + 1$ of these vector spaces. Moreover, function h having linear restrictions to the E_a's is necessarily defined as $h(x, y) = \begin{cases} Tr_1^m\left(xH\left(\frac{y}{x}\right)\right) \text{ if } x \neq 0 \\ Tr_1^m(\mu y) \text{ if } x = 0 \end{cases}$, $x, y \in \mathbb{F}_{2^m}$, for some mapping

H over $\mathbb{F}_{2^m}$ and some $\mu \in \mathbb{F}_{2^m}$. Then for every $(c, c') \in \mathbb{F}_{2^m} \times \mathbb{F}_{2^m}$ the set $I(c)$ equals $\{a \in \mathbb{F}_{2^m}; \forall x \in \mathbb{F}_{2^m}, Tr_1^m(xH(a)) = Tr_1^m(cx + c'ax)\} = \{a \in \mathbb{F}_{2^m}; H(a) = c + c'a\}$ if $c' \neq \mu$ and $\{a \in \mathbb{F}_{2^m}; H(a) = c + c'a\} \cup \{\infty\}$ if $c' = \mu$. Hence, the sets $I(c, c')$ depend on the pre-image of c by the mapping $H + c'Id$. The necessary and sufficient condition for h being bent is that, denoting $G(x) = H(x) + \mu x$, then G is a permutation and for every $c' \neq 0$ the function $G(x) + c'x$ is 2-to-1. Such bent functions have been first introduced by Dillon in [11]. He could exhibit in the class of such functions only the example of the function h in Corollary 3 below. But eight other examples have been found recently in [6] and lead to Corollary 4.

Corollary 3. *Let g be a function in the PS_{ap} class. Let i be any integer co-prime with m and $h(x, y) = Tr_1^m(xy^{2^i-1})$. Then the function $g + h$ is semi-bent.*

Indeed, h belongs to the Maiorana-McFarland class of bent functions since the function y^{2^i-1} is a permutation of $\mathbb{F}_{2^m}$, the restriction of h to E_a is linear for every a and its restriction to E_∞ is null.

Remark 1. According to [1, Theorem 6], the permutations y^{2^i-1} are the only permutations π such that $x\pi(x)$ is linear.

Corollary 4. *Let g be a function in the PS_{ap} class. Let h be one of the following functions:*

- $h(x, y) = Tr_1^m(x^{-5}y^6)$, $x, y \in \mathbb{F}_{2^m}$ *where m is odd;*
- $h(x, y) = Tr_1^m(x^{-3\cdot(2^k+1)}y^{3\cdot 2^k+4})$, $x, y \in \mathbb{F}_{2^m}$, *where $m = 2k - 1$;*
- $h(x, y) = Tr_1^m(x^{1-2^k-2^{2k}}y^{2^k+2^{2k}})$, $x, y \in \mathbb{F}_{2^m}$, *where $m = 4k - 1$;*
- $h(x, y) = Tr_1^m(x^{1-2^{2k+1}-2^{3k+1}}y^{2^{2k+1}+2^{3k+1}})$, $x, y \in \mathbb{F}_{2^m}$, *where $m = 4k + 1$;*
- $h(x, y) = Tr_1^m(x^{1-2^k}y^{2^k} + x^{-(2^k+1)}y^{2^k+2} + x^{-3\cdot(2^k+1)}y^{3\cdot 2^k+4})$, $x, y \in \mathbb{F}_{2^m}$, *where $m = 2k - 1$;*
- $h(x, y) = Tr_1^m(x^{\frac{5}{6}}y^{\frac{1}{6}} + x^{\frac{3}{6}}y^{\frac{3}{6}} + x^{\frac{1}{6}}y^{\frac{5}{6}})$, $x, y \in \mathbb{F}_{2^m}$, *where m is odd;*
- $h(x, y) = Tr_1^m\left(\left[\frac{\delta^2(x^{-3}+1)+\delta^2(1+\delta+\delta^2)(x^{-2}+x^{-1})}{x^{-4}+\delta^2x^{-2}+1} + x^{1/2}\right]\left[\frac{\delta^2(y^4+y)+\delta^2(1+\delta+\delta^2)(y^3+y^2)}{y^4+\delta^2y^2+1} + y^{1/2}\right]\right)$, $x, y \in \mathbb{F}_{2^m}$, *where $Tr_1^m(1/\delta) = 1$ and, if $m \equiv 2$ [mod 4], then $\delta \notin \mathbb{F}_4$;*
- $h(x, y) = Tr_1^m\left(x\,[A(x)]\,[B(y)]\right)$, $x, y \in \mathbb{F}_{2^m}$, *where m is even,*

$$A(x) = x^{-1/2} + \frac{1}{Tr_m^{2m}(b)}\left(Tr_m^{2m}(b^r)(x^{-1}+1)+\right.$$

$$\left.Tr_m^{2m}((bx^{-1}+b^{2^m})^r)(x^{-1}+Tr_m^{2m}(b)x^{-1/2}+1)^{1-r}\right)$$

$$B(y) = y^{1/2} + \frac{1}{Tr_m^{2m}(b)}\left(Tr_m^{2m}(b^r)(y+1)+\right.$$

$$\left.Tr_m^{2m}((by+b^{2^m})^r)(y+Tr_m^{2m}(b)y^{1/2}+1)^{1-r}\right)$$

$r = \pm\frac{2^m-1}{3}$, $b \in \mathbb{F}_{2^{2m}}$, $b^{2^m+1} = 1$ *and* $b \neq 1$.

Then the function $g + h$ is semi-bent.

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