3. Circulant modular Hadamard matrices of type 2

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Equivalently, this "remainder" $R(z)$ can be written

$$(11)\quad R(z) = 2\sum_{\nu=1}^{\frac{p-1}{2}}(z^{4\nu} + z^{-4\nu}) + \left\{\sum_{\nu=1}^{p}(z^{2\nu-1} + z^{-(2\nu-1)}) + z^p + z^{-p}\right\}\varepsilon_0\,\varepsilon_1 .$$

The (periodic) correlations of $H(z)$ in degrees $\equiv 2 \mod 4$ are strictly zero. This includes in particular the correlation of degree $2p$. Hence, the modular Hadamard matrix associated with the sequence (polynomial) of the Theorem is indeed of type 1 as asserted. The correlations in degrees $\equiv 0 \mod 4$ are $2(p-1)$. Note that the correlation in degree p is $2(p-1)\,\varepsilon_0\,\varepsilon_1$ because z^p+z^{-p} also appears in the sum $\sum_{\nu=1}^{p}(z^{2\nu-1} + z^{-(2\nu-1)})$ for $\nu = \frac{p+1}{2}$.

REMARK. It seems probable, from computer-assisted experimentation, that $p-1$ may be the maximum modulus for a modular circulant Hadamard matrix of type 1 and size $4p$. However, the power of 2 dividing $p-1$ is certainly not always maximal as the power of 2 dividing the modulus of a modular CHM of type 1 and size $4p$. There are many values of p (where p is prime and satisfies $p \equiv 9 \mod 16$) for which a variant of the formula for $H(z)$ in the above Theorem yields a 16-modular CHM. The first few such values of p are $p = 73,\ 89,\ 233,\ \ldots$. On the other hand, it seems for example that indeed no 16-modular, type 1 CHM of size $4p$ exists for $p = 41$.

We hope to come back on the general question of 16-modular circulant Hadamard matrices of type 1 in a future publication.

3. CIRCULANT MODULAR HADAMARD MATRICES OF TYPE 2

In this section we produce circulant modular Hadamard matrices of type 2 and size $n = 2(q+1)$, where q is an arbitrary odd prime power. The existence of such objects is a corollary of a theorem from the 1971 paper [DGS].

We are grateful to Roland Bacher for valuable discussions about some unpublished work of his which helped in obtaining the following result.

THEOREM 2. *For every $n = 2(q+1)$, where q is an odd prime power, there exists a binary sequence $X = (x_0, \ldots, x_{n-1})$ with $x_i = \pm 1$ for all i $(0 \leq i \leq n-1)$, such that $\gamma_k(X) = 0$ for all $k \neq 0, \frac{n}{2}$. In other words,* circ(X) *is a circulant modular Hadamard matrix of type 2 and size n.*

Proof. Set $x_{\frac{n}{2}} = x_0 = 1$ and $x_{\frac{n}{2}+i} = -x_i$ for all $i = 1, 2, \dots, \frac{n}{2} - 1$. The sequence $X = (x_1, x_2, \dots, x_{n-1})$ is therefore determined by its subsequence $Y = (x_1, x_2, \dots, x_{\frac{n}{2}-1})$.

We have $\gamma_0(X) = n$, $\gamma_{\frac{n}{2}}(X) = 4 - n$, and

$$\gamma_k(X) = 2(\alpha_k(Y) - \alpha_{\frac{n}{2}-k}(Y))$$

for all $k = 1, 2, \dots, \frac{n}{2} - 1$ as easily checked, where α_k is the kth *aperiodic* correlation coefficient. Of course, $\gamma_{n-k}(X) = \gamma_k(X)$ for all $k = 1, 2, \dots, \frac{n}{2} - 1$.

In order to prove the theorem, it therefore suffices to exhibit a binary sequence $Y = (x_1, x_2, \dots, x_{\frac{n}{2}-1})$ of length $\frac{n}{2} - 1 = q$, satisfying the equation $\alpha_k(Y) - \alpha_{\frac{n}{2}-k}(Y) = 0$ for every $k = 1, 2, \dots, \frac{n}{2} - 1$.

For this purpose, we recall the notion of a *negacyclic* matrix, introduced by Delsarte, Goethals and Seidel in their paper [DGS].

By definition it is simply a matrix of the form

$$\begin{pmatrix} u_0 & u_1 & \dots & \dots & u_r \\ -u_r & u_0 & u_1 & \dots & u_{r-1} \\ -u_{r-1} & -u_r & u_0 & \ddots & u_{r-2} \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ -u_1 & -u_2 & \dots & -u_r & u_0 \end{pmatrix}$$

which we will denote by $NC(u_0, u_1, \dots, u_r)$.

Explicitly, the entries $c_{i,j}$ of the matrix $NC(u_0, u_1, \dots, u_r)$ are

$$c_{i,j} = \begin{cases} u_{j-i} & \text{if } 0 \le i \le j \le r, \\ -u_{r-i+j+1} & \text{if } 0 \le j < i \le r. \end{cases}$$

It is very easy to see that the binary sequence $Y = (x_1, x_2, \dots, x_{\frac{n}{2}-1})$ satisfies $\alpha_k(Y) - \alpha_{\frac{n}{2}-k}(Y) = 0$ for every $k = 1, 2, \dots, \frac{n}{2} - 1$ if and only if the negacyclic matrix $C = NC(0, x_1, \dots, x_{\frac{n}{2}-1})$ is a conference matrix, that is if $C \cdot C^t = (\frac{n}{2} - 1)I$.

Now, Delsarte, Goethals and Seidel have explicitly constructed negacyclic conference matrices of every size of the form $q+1$, where $q = p^f$ with p an odd prime and f a positive integer, in Section 7 of [DGS]. These negacyclic conference matrices are equivalent to the usual Paley conference matrices based on the quadratic character $\chi \colon \mathbf{F}_q^* \to \{\pm 1\}$ of the finite field $\mathbf{F}_q$. □

NOTE. After having submitted the present paper for publication, we came across the Thèse d'Habilitation of Philippe Langevin (Toulon). There, a concept which is closely related to our type 2 sequences is studied. P. Langevin uses the terminology "almost perfect sequences" and his treatment also relies on [DGS].

Thus, we now find it preferable to drop the type 1 / type 2 terminology and rather call *enhanced modular* the modular matrices of type 1. We intend to use this new designation in future publications on the subject.

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