

CONVERGENCE OF CASCADE ALGORITHMS ASSOCIATED WITH NONHOMOGENEOUS REFINEMENT EQUATIONS

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ABSTRACT. This paper is devoted to a study of multivariate nonhomogeneous refinement equations of the form

$$\phi(x) = g(x) + \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\phi(Mx - \alpha), \quad x \in \mathbb{R}^s,$$

where $\phi = (\phi_1, \dots, \phi_r)^T$ is the unknown, $g = (g_1, \dots, g_r)^T$ is a given vector of functions on \mathbb{R}^s , M is an $s \times s$ dilation matrix, and a is a finitely supported refinement mask such that each $a(\alpha)$ is an $r \times r$ (complex) matrix. Let ϕ_0 be an initial vector in $(L_2(\mathbb{R}^s))^r$. The corresponding cascade algorithm is given by

$$\phi_k := g + \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\phi_{k-1}(M \cdot - \alpha), \quad k = 1, 2, \dots$$

In this paper we give a complete characterization for the L_2 -convergence of the cascade algorithm in terms of the refinement mask a , the nonhomogeneous term g , and the initial vector of functions ϕ_0 .

1. INTRODUCTION

A **nonhomogeneous refinement equation** is a functional equation of the form

$$(1.1) \quad \phi(x) = g(x) + \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\phi(Mx - \alpha), \quad x \in \mathbb{R}^s,$$

where $\phi = (\phi_1, \dots, \phi_r)^T$ is the unknown, $g = (g_1, \dots, g_r)^T$ is a given vector of functions on \mathbb{R}^s , M is an $s \times s$ dilation matrix, and a is a finitely supported mask such that each $a(\alpha)$ is an $r \times r$ (complex) matrix. In this paper, by a **dilation matrix** we mean an integer matrix whose eigenvalues lie outside the closed unit disk. When $g = 0$, (1.1) becomes the **homogeneous refinement equation**

$$\phi(x) = \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\phi(Mx - \alpha), \quad x \in \mathbb{R}^s.$$

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The readers are referred to [1] and [4] for some basic properties of homogeneous refinement equations. For vector homogeneous refinement equations, see [9], [2], [22], [19], and [27].

Nonhomogeneous refinement equations generalized from their homogeneous counterpart are motivated by constructions of multiwavelets to obtain multi-channel filters with good time-frequency localization in the area of signal processing and constructions of wavelets on a finite interval to find numerical solutions of differential equations in the area of numerical analysis (see, e.g., [24] and [3]). A systematic study of such refinement equations not only complements the existing literature of its homogeneous counterpart, but also provides a global view of the subject. This further leads to a better understanding of refinement equations.

For a given equation (1.1), the first problem to consider is whether it has distributional solutions. Distributional solutions of the nonhomogeneous refinement equation (1.1) were studied in [5], [25], [6], [15], and [26]. In [15], we provided a characterization of the existence of distributional solutions for continuous and discrete nonhomogeneous refinement equations.

In practice, solutions are required to be functions with certain smoothness. Since solutions are not of any analytic form in many cases, the cascade algorithm is used to obtain approximations of the solutions. The second problem to consider is the L_2 -convergence of the cascade algorithm, which will be the main topic of this paper. The convergence of the cascade algorithm is fundamental to wavelet theory and subdivision. For example, in the context of wavelet theory, the key step to the construction is to find right refinable functions, and in the context of subdivision, the limiting surface of the subdivision process is a linear combination of shifts of the refinable function corresponding to the subdivision scheme.

Suppose $g = (g_1, \dots, g_r)^T$ is a given $r \times 1$ vector of compactly supported functions in $L_2(\mathbb{R}^s)$. Let Q_a be the **cascade operator** on $(L_2(\mathbb{R}^s))^r$ given by

$$(1.2) \quad Q_a f := \sum_{\alpha \in \mathbb{Z}^s} a(\alpha) f(M \cdot - \alpha), \quad f = (f_1, \dots, f_r)^T \in (L_2(\mathbb{R}^s))^r.$$

Choose an initial vector $\phi_0 \in (L_2(\mathbb{R}^s))^r$. Let

$$(1.3) \quad \phi_k := g + \sum_{\alpha \in \mathbb{Z}^s} a(\alpha) \phi_{k-1}(M \cdot - \alpha), \quad k = 1, 2, \dots$$

If there exists an $r \times 1$ vector of functions $\phi \in (L_2(\mathbb{R}^s))^r$ such that

$$\lim_{k \rightarrow \infty} \|\phi_k - \phi\|_{(L_2(\mathbb{R}^s))^r} = 0,$$

then we say that the **cascade algorithm** associated with a, g , and ϕ_0 is L_2 -convergent. If this is the case, then the limit ϕ is a solution of the nonhomogeneous refinement equation (1.1). In the scalar case ($r = 1$), we say that the cascade algorithm associated with the corresponding homogeneous equation converges if it converges for any initial function ϕ_0 that satisfies

$$(1.4) \quad \sum_{\alpha \in \mathbb{Z}^s} \phi_0(\cdot - \alpha) = 1.$$

The L_2 -convergence of cascade algorithms associated with homogeneous refinement equations were investigated in many papers such as [11], [23], [8], [20], [22] and [16]. As it has been done in many other areas of mathematics, to solve the nonhomogeneous problem, one starts with the corresponding homogeneous problem and uses the results of this case as indicators and the methods as a starting

point. This process normally is nontrivial, since the nonhomogeneous problem cannot be reduced to the homogeneous problem entirely. This is also the case for the convergence of the cascade algorithm as shown in the following two examples.

The first example shows that in the nonhomogeneous case, the choice of the initial functions highly depends on the nonhomogeneous term.

Example 1.1. Let $M = (2)$, $a(0) = a(1) = 1$, $a(\alpha) = 0$ for all $\alpha \in \mathbb{Z} \setminus \{0, 1\}$, and the nonhomogeneous term $g = \chi_{[0,1/4)} + 2\chi_{[1/4,1/2)} + \chi_{[3/4,1)} - \chi_{[1,2)}$, where χ_E denotes the characteristic function of the set E . It is clear that the cascade algorithm associated with the homogeneous equation converges for any initial function satisfies (1.4). However, since $\sum_{\alpha \in \mathbb{Z}} g(\cdot - \alpha) \neq 0$, the cascade algorithm associated with the nonhomogeneous equation does not converge for any initial function satisfying (1.4) by Remark 2.7. It converges when $\phi_0 = \chi_{[0,1/2)}$. \square

Assume that the cascade algorithm associated with the homogeneous case converges. Corollary 2.6 provides a complete characterization of the initial functions for which the cascade algorithm associated with the nonhomogeneous refinement equation converges. However, the next example shows that the convergence of the cascade algorithm associated with the homogeneous refinement equation is not a necessary condition for the convergence of the cascade algorithm associated with the nonhomogeneous one. Hence, it is necessary to give a complete characterization in terms of the refinement mask a , the nonhomogeneous term g and the initial vector of functions ϕ_0 for the convergence of the cascade algorithm in the nonhomogeneous case. Such a characterization will be given in Theorem 2.4.

Example 1.2. Consider the nonhomogeneous refinement equation

$$\phi = a(\phi(2\cdot) + \phi(2\cdot - 1)) + g,$$

where $1 < a < \sqrt{2}$ and $g = \chi_{[0,1)} - \chi_{[1,2)}$. Clearly, the cascade algorithm associated with the corresponding homogeneous refinement equation does not converge in L_2 -norm. On the other hand, since $\sum_{\alpha \in \mathbb{Z}} g(\cdot - \alpha) = 0$, the cascade algorithm associated with the nonhomogeneous refinement equation does converge for any initial function ϕ_0 supported in $[0, 2]$ that satisfies $\sum_{\alpha \in \mathbb{Z}} \phi_0(\cdot - \alpha) = 0$ as shown in Example 3.2. \square

In the univariate and scalar case ($s = 1$ and $r = 1$), a characterization of L_2 -convergence was given in [25] for cascade algorithms associated with the nonhomogeneous refinement equation (1.1). Their argument is based on the fact established in [12] that a compactly supported function on \mathbb{R} is a linear combination of finitely many shifts of a compactly supported function whose shifts are linearly independent. However, multivariate compactly supported functions do *not* have such property (see [13] for a counterexample). Thus, a new technique has to be introduced to deal with the multivariate case.

The purpose of this paper is to give a complete characterization for the L_2 -convergence of cascade algorithms in terms of the refinement mask a , the nonhomogeneous term g , and the initial vector of functions ϕ_0 . This will be done in Section 2. In Section 2, we also discuss some relation between the L_2 -convergences of cascade algorithms associated with the homogeneous and nonhomogeneous refinement equations. In Section 3, we give several examples to illustrate the general theory.

2. CONVERGENCE OF CASCADE ALGORITHMS

In this section we give a characterization for the L_2 -convergence of the cascade algorithm associated with a nonhomogeneous refinement equation.

As usual, we use $L_2(\mathbb{R}^s)$ to denote the space of square integrable functions on \mathbb{R}^s . The norm on $L_2(\mathbb{R}^s)$ is given by

$$\|f\|_2 := \left(\int_{\mathbb{R}^s} |f(x)|^2 dx \right)^{1/2}, \quad f \in L_2(\mathbb{R}^s).$$

Given a measurable function f on \mathbb{R}^s , we use $\|f\|_\infty$ to denote the essential supremum of $|f|$ on \mathbb{R}^s .

For two functions f, h in $L_2(\mathbb{R}^s)$, $f \odot h$ is defined as follows:

$$f \odot h(x) := \int_{\mathbb{R}^s} f(x+y) \overline{h(y)} dy, \quad x \in \mathbb{R}^s,$$

where $\overline{h(y)}$ denotes the complex conjugate of $h(y)$. In other words, $f \odot h$ is the convolution of f with the function $y \mapsto \overline{h(-y)}$, $y \in \mathbb{R}^s$. We find that this notation, which was introduced in [14], is convenient. It is easily seen that $f \odot h$ lies in $C_0(\mathbb{R}^s)$, the space of continuous functions on \mathbb{R}^s which vanish at ∞ . In particular, $f \odot h$ is uniformly continuous. Clearly,

$$(2.1) \quad \|f \odot h\|_\infty \leq \|f\|_2 \|h\|_2.$$

Moreover, $(f \odot f)(0) = \|f\|_2^2$.

Let $\ell_0(\mathbb{Z}^s)$ denote the linear space of all finitely supported sequences on \mathbb{Z}^s , and let $\ell_\infty(\mathbb{Z}^s)$ denote the linear space of all bounded sequences on \mathbb{Z}^s . The norm on $\ell_\infty(\mathbb{Z}^s)$ is given by $\|v\|_\infty := \sup\{|v(\alpha)| : \alpha \in \mathbb{Z}^s\}$, $v \in \ell_\infty(\mathbb{Z}^s)$.

We use \mathbb{C}^r to denote the linear space of all $r \times 1$ complex vectors. The norm of a vector $\xi = (\xi_1, \dots, \xi_r)^T \in \mathbb{C}^r$ is defined by $|\xi| := \sum_{j=1}^r |\xi_j|$. If F is a linear space, we use F^r to denote the linear space

$$\{(f_1, \dots, f_r)^T : f_1, \dots, f_r \in F\}.$$

If, in addition, F is a Banach space equipped with the norm $\|\cdot\|$, then F^r is also a Banach space with the norm given by

$$\|f\| := \sum_{j=1}^r \|f_j\|, \quad f = (f_1, \dots, f_r)^T \in F^r.$$

The Kronecker product of two matrices is a useful tool in the study of vector refinement equations (see [7], [17] and [18]). Let us recall some basic properties of the Kronecker product from [10]. Suppose $A = (a_{ij})_{1 \leq i \leq m, 1 \leq j \leq n}$ and $B = (b_{ij})_{1 \leq i \leq k, 1 \leq j \leq l}$ are two matrices. The (right) Kronecker product of A and B , written $A \otimes B$, is defined to be the block matrix

$$A \otimes B := \begin{bmatrix} a_{11}B & a_{12}B & \cdots & a_{1n}B \\ a_{21}B & a_{22}B & \cdots & a_{2n}B \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}B & a_{m2}B & \cdots & a_{mn}B \end{bmatrix}.$$

For three matrices A, B , and C of the same type, we have

$$\begin{aligned} (A+B) \otimes C &= (A \otimes C) + (B \otimes C), \\ A \otimes (B+C) &= (A \otimes B) + (A \otimes C). \end{aligned}$$

If A, B, C, D are four matrices such that the products AC and BD are well defined, then

$$(A \otimes B)(C \otimes D) = (AC) \otimes (BD).$$

Moreover, if $\lambda_1, \dots, \lambda_r$ are the eigenvalues of an $r \times r$ matrix A and μ_1, \dots, μ_r are the eigenvalues of an $r \times r$ matrix B , then the eigenvalues of $A \otimes B$ are $\lambda_j \mu_k$, $j, k = 1, \dots, r$.

The vector $(a_{11}, \dots, a_{r1}, a_{12}, \dots, a_{r2}, \dots, a_{1r}, \dots, a_{rr})^T$ is said to be the vec-function of A and written as $\text{vec}A$ for a matrix $A = (a_{ij})_{1 \leq i, j \leq r}$. Suppose A, X , and B are three $r \times r$ matrices. Then we have (see [10])

$$(2.2) \quad \text{vec}(AXB) = (B^T \otimes A) \text{vec} X.$$

Suppose $\phi = (\phi_1, \dots, \phi_r)^T$ and $\psi = (\psi_1, \dots, \psi_r)^T$ lie in $(L_2(\mathbb{R}^s))^r$. Let $\phi \odot \psi^T$ be defined as follows:

$$\phi \odot \psi^T := \begin{bmatrix} \phi_1 \odot \psi_1 & \phi_1 \odot \psi_2 & \cdots & \phi_1 \odot \psi_r \\ \phi_2 \odot \psi_1 & \phi_2 \odot \psi_2 & \cdots & \phi_2 \odot \psi_r \\ \vdots & \vdots & \ddots & \vdots \\ \phi_r \odot \psi_1 & \phi_r \odot \psi_2 & \cdots & \phi_r \odot \psi_r \end{bmatrix}.$$

By (2.1) we have

$$(2.3) \quad \|\text{vec}(\phi \odot \psi^T)\|_\infty \leq \|\phi\|_2 \|\psi\|_2.$$

Moreover,

$$|\text{vec}(\phi \odot \phi^T)(0)| = \sum_{j=1}^r \sum_{k=1}^r |\phi_j \odot \phi_k(0)| \geq \sum_{j=1}^r |\phi_j \odot \phi_j(0)| = \sum_{j=1}^r \|\phi_j\|_2^2.$$

Consequently,

$$(2.4) \quad |\text{vec}(\phi \odot \phi^T)(0)| \geq \frac{1}{r} \|\phi\|_2^2.$$

Now let us discuss properties of the cascade operator defined in (1.2).

Lemma 2.1. *Let a_k ($k = 1, 2, \dots$) be the sequences of $r \times r$ matrices defined by $a_1 := a$ and*

$$a_k(\alpha) = \sum_{\beta \in \mathbb{Z}^s} a_{k-1}(\beta) a(\alpha - M\beta), \quad \alpha \in \mathbb{Z}^s, k = 2, 3, \dots$$

Then the following formula is valid for all $k = 1, 2, \dots$ and all $f \in (L_2(\mathbb{R}^s))^r$:

$$(2.5) \quad Q_a^k f = \sum_{\alpha \in \mathbb{Z}^s} a_k(\alpha) f(M^k \cdot - \alpha).$$

Proof. The proof proceeds by induction on k . For $k = 1$, (2.5) comes from the definition of the cascade operator Q_a . Suppose $k > 1$ and (2.5) has been verified

for $k - 1$. Then by the induction hypothesis we have

$$\begin{aligned}
Q_a^k f &= Q_a^{k-1}(Q_a f) = \sum_{\beta \in \mathbb{Z}^s} a_{k-1}(\beta)(Q_a f)(M^{k-1} \cdot - \beta) \\
&= \sum_{\beta \in \mathbb{Z}^s} \sum_{\alpha \in \mathbb{Z}^s} a_{k-1}(\beta) a(\alpha) f(M^k \cdot - M\beta - \alpha) \\
&= \sum_{\alpha \in \mathbb{Z}^s} \left[\sum_{\beta \in \mathbb{Z}^s} a_{k-1}(\beta) a(\alpha - M\beta) \right] f(M^k \cdot - \alpha) \\
&= \sum_{\alpha \in \mathbb{Z}^s} a_k(\alpha) f(M^k \cdot - \alpha).
\end{aligned}$$

This completes the induction procedure. \square

Lemma 2.2. *The following relation is valid for all $k = 1, 2, \dots$ and all $f \in (L_2(\mathbb{R}^s))^r$:*

$$\text{vec}((Q_a^k f) \odot (Q_a^k f)^T) = Q_b^k(\text{vec}(f \odot f^T)),$$

where b is given by

$$(2.6) \quad b(\alpha) = \sum_{\beta \in \mathbb{Z}^s} \overline{a(\beta)} \otimes a(\alpha + \beta) / |\det M|, \quad \alpha \in \mathbb{Z}^s.$$

Proof. Write m for $|\det M|$. It is easily seen that

$$f(M^k \cdot - \alpha) \odot f^T(M^k \cdot - \beta) = \frac{1}{m^k} (f \odot f^T)(M^k \cdot - \alpha + \beta), \quad \alpha, \beta \in \mathbb{Z}^s.$$

By (2.5) it follows that

$$\begin{aligned}
(Q_a^k f) \odot (Q_a^k f)^T &= \left[\sum_{\alpha \in \mathbb{Z}^s} a_k(\alpha) f(M^k \cdot - \alpha) \right] \odot \left[\sum_{\beta \in \mathbb{Z}^s} a_k(\beta) f(M^k \cdot - \beta) \right]^T \\
&= \frac{1}{m^k} \sum_{\alpha \in \mathbb{Z}^s} \sum_{\beta \in \mathbb{Z}^s} a_k(\alpha) (f \odot f^T)(M^k \cdot - \alpha + \beta) \overline{a_k(\beta)}^T.
\end{aligned}$$

Therefore, with $h := \text{vec}(f \odot f^T)$, by (2.2) we obtain

$$\begin{aligned}
\text{vec}((Q_a^k f) \odot (Q_a^k f)^T) &= \frac{1}{m^k} \sum_{\alpha \in \mathbb{Z}^s} \sum_{\beta \in \mathbb{Z}^s} \overline{a_k(\beta)} \otimes a_k(\alpha) h(M^k \cdot - \alpha + \beta) \\
&= \frac{1}{m^k} \sum_{\alpha \in \mathbb{Z}^s} \sum_{\beta \in \mathbb{Z}^s} \overline{a_k(\beta)} \otimes a_k(\alpha + \beta) h(M^k \cdot - \alpha).
\end{aligned}$$

Let b_k ($k = 1, 2, \dots$) be the sequences of $r^2 \times r^2$ matrices defined by $b_1 := b$ and

$$b_k(\alpha) = \sum_{\beta \in \mathbb{Z}^s} b_{k-1}(\beta) b(\alpha - M\beta), \quad \alpha \in \mathbb{Z}^s, \quad k = 2, 3, \dots$$

Then one can show as in the proof of (2.5) that

$$Q_b^k h = \sum_{\alpha \in \mathbb{Z}^s} b_k(\alpha) h(M^k \cdot - \alpha).$$

To complete the proof of Lemma 2.2, it suffices to show

$$(2.7) \quad b_k(\alpha) = \frac{1}{m^k} \sum_{\beta \in \mathbb{Z}^s} \overline{a_k(\beta)} \otimes a_k(\alpha + \beta) \quad \forall \alpha \in \mathbb{Z}^s.$$

This will be done by induction on k . By the definitions of a_1 and b_1 , (2.7) is true for $k = 1$. Suppose $k > 1$ and (2.7) has been verified for $k - 1$. By the induction hypothesis, for $\alpha \in \mathbb{Z}^s$ we have

$$\begin{aligned} b_k(\alpha) &= \sum_{\eta \in \mathbb{Z}^s} b_{k-1}(\eta)b(\alpha - M\eta) \\ &= m^{-k} \sum_{\beta \in \mathbb{Z}^s} \sum_{\gamma \in \mathbb{Z}^s} \sum_{\eta \in \mathbb{Z}^s} (\overline{a_{k-1}(\gamma)} \otimes a_{k-1}(\eta + \gamma)) (\overline{a(\beta)} \otimes a(\alpha - M\eta + \beta)) \\ &= m^{-k} \sum_{\beta \in \mathbb{Z}^s} \sum_{\gamma \in \mathbb{Z}^s} \sum_{\eta \in \mathbb{Z}^s} (\overline{a_{k-1}(\gamma)} a(\beta - M\gamma)) \otimes (a_{k-1}(\eta) a(\alpha + \beta - M\eta)) \\ &= m^{-k} \sum_{\beta \in \mathbb{Z}^s} \overline{a_k(\beta)} \otimes a_k(\alpha + \beta). \end{aligned}$$

This completes the induction procedure, and thereby finishes the proof of Lemma 2.2. \square

Let T_b be the **transition operator** on $(\ell_0(\mathbb{Z}^s))^{r^2}$ given by

$$T_b v(\alpha) := \sum_{\beta \in \mathbb{Z}^s} b(M\alpha - \beta)v(\beta), \quad \alpha \in \mathbb{Z}^s, v \in (\ell_0(\mathbb{Z}^s))^{r^2}.$$

It is known that the minimal invariant subspace V of T_b generated by v is finite dimensional (see [8] and [16]). We use $\rho(T_b|_V)$ to denote the spectral radius of $T_b|_V$.

Lemma 2.3. *The following relation is valid for all $k = 1, 2, \dots$ and all $v \in (\ell_0(\mathbb{Z}^s))^{r^2}$:*

$$T_b^k v(\alpha) = \sum_{\beta \in \mathbb{Z}^s} b_k(M^k \alpha - \beta)v(\beta), \quad \alpha \in \mathbb{Z}^s, k = 1, 2, \dots$$

Proof. The proof proceeds by induction on k . By the definition of T_b , our claim is true for $k = 1$. Suppose it is valid for $k - 1$. By the induction hypothesis, for $\alpha \in \mathbb{Z}^s$ we have

$$\begin{aligned} T_b^k v(\alpha) &= T_b^{k-1}(T_b v)(\alpha) \\ &= \sum_{\beta \in \mathbb{Z}^s} b_{k-1}(M^{k-1}\alpha - \beta)(T_b v)(\beta) \\ &= \sum_{\beta \in \mathbb{Z}^s} \sum_{\gamma \in \mathbb{Z}^s} b_{k-1}(M^{k-1}\alpha - \beta)b(M\beta - \gamma)v(\gamma) \\ &= \sum_{\gamma \in \mathbb{Z}^s} \left[\sum_{\beta \in \mathbb{Z}^s} b_{k-1}(\beta)b(M^k \alpha - \gamma - M\beta) \right] v(\gamma) \\ &= \sum_{\gamma \in \mathbb{Z}^s} b_k(M^k \alpha - \gamma)v(\gamma). \end{aligned}$$

The proof of Lemma 2.3 is complete. \square

Let us investigate the cascade algorithm as given in (1.3). For $k = 1, 2, \dots$, by (1.2) and (1.3) we have $\phi_k = g + Q_a g + \dots + Q_a^{k-1} g + Q_a^k \phi_0$. It follows that

$$(2.8) \quad \phi_{k+1} - \phi_k = Q_a^k g + Q_a^{k+1} \phi_0 - Q_a^k \phi_0 = Q_a^k g_0,$$

where $g_0 := g + Q_a \phi_0 - \phi_0$. The following theorem gives a characterization for the L_2 -convergence of the cascade algorithm associated with (1.1).

Theorem 2.4. *The cascade algorithm associated with a , g , and ϕ_0 converges in the L_2 -norm if and only if $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$, where b is given by (2.6) and v is given by $v(\alpha) = \text{vec}(g_0 \odot g_0^T)(\alpha)$, $g_0 = g + Q_a \phi_0 - \phi_0$, $\alpha \in \mathbb{Z}^s$, or equivalently, $\rho(T_b|_V) < 1$, where V is the minimal invariant subspace of T_b generated by v .*

Proof. Let us first establish the sufficiency part of the theorem. Write h_0 for $\text{vec}(g_0 \odot g_0^T)$ and h_k for $\text{vec}((Q_a^k g_0) \odot (Q_a^k g_0)^T)$, $k = 1, 2, \dots$. Then $v(\alpha) = h_0(\alpha)$ for all $\alpha \in \mathbb{Z}^s$. By Lemma 2.2 we have $h_k = Q_b^k h_0$, $k = 1, 2, \dots$. An application of (2.4) gives

$$\|Q_a^k g_0\|_2^2 \leq r |\text{vec}((Q_a^k g_0) \odot (Q_a^k g_0)^T)(0)| = r |h_k(0)|.$$

For $\alpha \in \mathbb{Z}^s$, by Lemma 2.3 and Lemma 2.2 we have

$$(2.9) \quad T_b^k v(\alpha) = \sum_{\beta \in \mathbb{Z}^s} b_k(M^k \alpha - \beta) v(\beta) = \sum_{\beta \in \mathbb{Z}^s} b_k(\beta) h_0(M^k \alpha - \beta) = Q_b^k h_0(\alpha).$$

In particular, $h_k(0) = Q_b^k h_0(0) = T_b^k v(0)$. If $\rho(T_b|_V) < 1$, then there exists some η , $0 < \eta < 1$, and a constant $C > 0$ such that $|T_b^k v(0)| \leq \|T_b^k v\|_\infty \leq C \eta^k$. Consequently,

$$\|Q_a^k g_0\|_2^2 \leq r |h_k(0)| = r |Q_b^k h_0(0)| = r |T_b^k v(0)| \leq C r \eta^k, \quad k = 1, 2, \dots$$

In light of (2.8), we have $\phi_{k+1} - \phi_k = Q_a^k g_0$. Since $\eta < 1$, $(\phi_k)_{k=1,2,\dots}$ is a Cauchy sequence in $(L_2(\mathbb{R}^s))^r$. Therefore, the cascade algorithm converges in the L_2 -norm.

Next, we establish the necessity part of the theorem. By Lemma 2.2 and (2.3) we obtain

$$|Q_b^k h_0(\alpha)| = |\text{vec}((Q_a^k g_0) \odot (Q_a^k g_0)^T)(\alpha)| \leq \|Q_a^k g_0\|_2^2 \quad \forall \alpha \in \mathbb{Z}^s.$$

This in connection with (2.9) gives $\|T_b^k v\|_\infty \leq \|Q_a^k g_0\|_2^2$. If the cascade algorithm converges in the L_2 -norm, then $\lim_{k \rightarrow \infty} \|Q_a^k g_0\|_2^2 = 0$. Hence, $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$. Consequently, $\rho(T_b|_V) < 1$. \square

Remark 2.5. Let K be a compact subset of \mathbb{R}^s containing $\text{supp } b := \{\alpha \in \mathbb{Z}^s : b(\alpha) \neq 0\}$, and let $\Omega := (\sum_{n=1}^{\infty} M^{-n} K) \cap \mathbb{Z}^s$. Choose K properly so that Ω contains the support of v , where v is given by $v(\alpha) = \text{vec}(g_0 \odot g_0^T)(\alpha)$, $\alpha \in \mathbb{Z}^s$. Let \mathcal{T}_b be the matrix $(b(M\alpha - \beta))_{\alpha, \beta \in \Omega}$. If $\rho(\mathcal{T}_b) < 1$, then $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$. Hence, the cascade algorithm associated with a , g , and any initial choice of ϕ_0 is L_2 -convergent. Suppose $\rho(\mathcal{T}_b) \geq 1$. Let U be a nonsingular matrix satisfying $\mathcal{T}_b = U^{-1} \text{diag}(A_1, A_2) U$, where A_1 and A_2 are two square matrices such that $\rho(A_1) < 1$ and the eigenvalues of A_2 lie outside the open unit disk. Suppose A_2 is an $m_2 \times m_2$ matrix. Then $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$ if and only if

$$(2.10) \quad U_2 (v(\beta))_{\beta \in \Omega} = 0,$$

where U_2 is the matrix consisting of the last m_2 rows of U . Therefore, the cascade algorithm associated with a , g , and ϕ_0 is L_2 -convergent if and only if (2.10) is true. \square

Next we will show that for a special set of vectors of compactly supported functions $g \in (L_2(\mathbb{R}^s))^r$ the corresponding cascade algorithm converges as long as the cascade algorithm corresponding to the homogeneous refinement equation converges.

For this purpose, consider the homogeneous refinement equation

$$(2.11) \quad \varphi = \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\varphi(M \cdot - \alpha).$$

Assume that $|\det M|$ is a simple eigenvalue of the matrix $\sum_{\alpha \in \mathbb{Z}^s} a(\alpha)$ with a left row eigenvector y . We say that the cascade algorithm associated with the homogeneous refinement equation with mask a , converges (in the L_2 -norm) whenever for any compactly supported $\varphi_0 \in (L_2(\mathbb{R}^s))^r$ satisfying

$$y \sum_{\alpha \in \mathbb{Z}^s} \varphi_0(\cdot - \alpha) = y,$$

the sequence φ_k defined by $\varphi_k = \sum_{\alpha \in \mathbb{Z}^s} a(\alpha)\varphi_{k-1}(M \cdot - \alpha)$, $k = 1, 2, \dots$, converges in the L_2 -norm.

Corollary 2.6. *Assume that $|\det M|$ is a simple eigenvalue of the matrix $\sum_{\alpha \in \mathbb{Z}^s} a(\alpha)$ with a left row eigenvector y . Assume that the cascade algorithm associated with the homogeneous refinement equation with mask a converges in the L_2 -norm. Then the cascade algorithm associated with a , g , and ϕ_0 converges in the L_2 -norm if and only if g and ϕ_0 satisfy*

$$(2.12) \quad y \left(\sum_{\alpha \in \mathbb{Z}^s} (g_0 \odot g_0^T)(\alpha) \right) \bar{y}^T = 0,$$

where $g_0 = g + Q_a \phi_0 - \phi_0$.

Proof. If the cascade algorithm associated with the homogeneous refinement equation with mask a converges in the L_2 -norm, then 1 is a simple eigenvalue of T_b and the other eigenvalues of T_b lie inside the open unit disc (see [20] and [22]). Furthermore, the space V defined by

$$V := \left\{ u \in (\ell_0(\mathbb{Z}^s))^{r^2} : (\bar{y} \otimes y) \sum_{\alpha \in \mathbb{Z}^s} u(\alpha) = 0 \right\}$$

is invariant under T_b and $\rho(T_b|_V) < 1$ (see [8] and [14]). Let v be the element in $(\ell_0(\mathbb{Z}^s))^{r^2}$ defined by $v(\alpha) := \text{vec}(g_0 \odot g_0^T)(\alpha)$, $\alpha \in \mathbb{Z}^s$. In light of (2.2), it follows from (2.12) that v lies in V . Hence, $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$. By Theorem 2.4, the cascade algorithm associated with a , g , and ϕ_0 converges in the L_2 -norm.

Conversely, assume that the cascade algorithm associated with a , g and ϕ_0 converges. Let $w(\alpha) := \text{vec}(\varphi \odot \varphi^T)(\alpha)$, $\alpha \in \mathbb{Z}^s$, where φ is the solution of the homogeneous refinement equation with mask a such that $y\hat{\varphi}(0) = 1$. Then w is an eigenvector of T_b corresponding to eigenvalue 1 with $(\bar{y} \otimes y) \sum_{\alpha \in \mathbb{Z}^s} w(\alpha) = 1$.

Recall that v is the element in $(\ell_0(\mathbb{Z}^s))^{r^2}$ defined by $v(\alpha) := \text{vec}(g_0 \odot g_0^T)(\alpha)$, $\alpha \in \mathbb{Z}^s$. There exist $c \in \mathbb{C}$ and $u \in V$ such that $v = cw + u$. We have $\lim_{k \rightarrow \infty} \|T_b^k u\|_\infty = 0$. Since the cascade algorithm associated with a , g and ϕ_0 converges in the L_2 -norm, we also have $\lim_{k \rightarrow \infty} \|T_b^k v\|_\infty = 0$, by Theorem 2.4. However, $T_b w = w$. Hence,

$$T_b^k v = cw + T_b^k u, \quad k = 1, 2, \dots$$

Letting $k \rightarrow \infty$ in the above equation, we obtain $c = 0$. Consequently, $v = u$ lies in V . In other words, (2.12) holds true. \square

Remark 2.7. In Corollary 2.6, condition (2.12) is equivalent to $y \sum_{\alpha \in \mathbb{Z}^s} g_0(\cdot - \alpha) = 0$. Assume that $y \sum_{\alpha \in \mathbb{Z}^s} \phi_0(\cdot - \alpha) = y$. Then, the cascade algorithm associated with nonhomogeneous equation converges if and only if $y \sum_{\alpha \in \mathbb{Z}^s} g(\cdot - \alpha) = 0$.

3. EXAMPLES

In this section we give several examples to illustrate our theory.

Example 3.1. Consider the nonhomogeneous refinement equation

$$(3.1) \quad \phi(x) = t\phi(2x) + g(x), \quad x \in \mathbb{R},$$

where t is a nonzero complex number and g is a compactly supported function in $L_2(\mathbb{R})$. Let ϕ_0 be a compactly supported function in $L_2(\mathbb{R})$. The corresponding cascade algorithm is given by $\phi_k = t\phi_{k-1}(2\cdot) + g, k = 1, 2, \dots$. We have $a(0) = t$ and $a(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus \{0\}$. Let b be the sequence given by (2.6). Then $b(0) = |t|^2/2$ and $b(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus \{0\}$. Let $g_0 := g + t\phi_0(2\cdot) - \phi_0$ and $v(\alpha) := (g_0 \odot g_0)(\alpha)$ for $\alpha \in \mathbb{Z}$. Then for sufficiently large k we have

$$T_b^k v(0) = (|t|^2/2)^k v(0) \quad \text{and} \quad T_b^k v(\alpha) = 0 \quad \forall \alpha \in \mathbb{Z} \setminus \{0\}.$$

Note that $v(0) = \|g_0\|_2^2$. Hence, $v(0) = 0$ if and only if $g_0 = 0$. If $|t| < \sqrt{2}$, then Theorem 2.4 tells us that the cascade algorithm associated with a, g , and any ϕ_0 is L_2 -convergent. If $|t| \geq \sqrt{2}$, then the cascade algorithm converges in the L_2 -norm if and only if ϕ_0 is the solution of the equation (3.1).

This example was also considered in [21] and [25]. □

Example 3.2. Consider the nonhomogeneous refinement equation

$$(3.2) \quad \phi(x) = a_0\phi(2x) + a_1\phi(2x - 1) + g(x), \quad x \in \mathbb{R},$$

where a_0, a_1 are two nonzero complex numbers and g is a function in $L_2(\mathbb{R})$ supported in $[0, 2]$. Let ϕ_0 be a function in $L_2(\mathbb{R})$ supported in $[0, 2]$. The corresponding cascade algorithm is given by

$$\phi_k = a_0\phi_{k-1}(2\cdot) + a_1\phi_{k-1}(2\cdot - 1) + g, \quad k = 1, 2, \dots$$

We have $a(0) = a_0, a(1) = a_1$ and $a(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus \{0, 1\}$. Let b be the sequence given by (2.6). Then $b(-1) = a_0\bar{a}_1/2, b(0) = (|a_0|^2 + |a_1|^2)/2, b(1) = \bar{a}_0a_1/2$ and $b(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus \{-1, 0, 1\}$. Let $g_0 := g + a_0\phi_0(2\cdot) + a_1\phi_0(2\cdot - 1) - \phi_0$ and $v(\alpha) := (g_0 \odot g_0)(\alpha)$ for $\alpha \in \mathbb{Z}$. Then g_0 is supported in $[0, 2]$ and $v(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus \{-1, 0, 1\}$.

Let \mathcal{T}_b be the matrix $(b(2i - j))_{-1 \leq i, j \leq 1}$; that is,

$$(3.3) \quad \mathcal{T}_b = \begin{bmatrix} b(-1) & 0 & 0 \\ b(1) & b(0) & b(-1) \\ 0 & 0 & b(1) \end{bmatrix}.$$

The eigenvalues of \mathcal{T}_b are $a_0\bar{a}_1/2, \bar{a}_0a_1/2$ and $(|a_0|^2 + |a_1|^2)/2$. If $|a_0|^2 + |a_1|^2 < 2$, then $\rho(\mathcal{T}_b) < 1$. Hence the cascade algorithm associated with $\{a_0, a_1\}, g$ and ϕ_0 is L_2 -convergent. If $|a_0a_1| \geq 2$, then each eigenvalue of \mathcal{T}_b lies outside the open unit disk. Therefore the cascade algorithm associated with $\{a_0, a_1\}, g$ and ϕ_0 is L_2 -convergent if and only if ϕ_0 is the L_2 -solution of (3.2).

Finally, we consider the case $|a_0a_1| < 2 \leq |a_0|^2 + |a_1|^2$. Let

$$U := \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ p & 1 & \bar{p} \end{bmatrix},$$

where $p := b(1)/(b(0) - b(-1)) = \bar{a}_0a_1/(|a_0|^2 + |a_1|^2 - a_0\bar{a}_1)$. Then

$$\mathcal{T}_b = U^{-1} \text{diag}(b(-1), b(1), b(0))U.$$

By Theorem 2.4 and Remark 2.5, we conclude that the cascade algorithm associated with $\{a_0, a_1\}, g$ and ϕ_0 is L_2 -convergent if and only if g and ϕ_0 satisfy

$$(3.4) \quad p(g_0 \odot g_0)(-1) + \bar{p}(g_0 \odot g_0)(1) + \|g_0\|_2^2 = 0.$$

Assume $a_0 = a_1 = a$ with $1 \leq |a| < \sqrt{2}$; then p and \bar{p} in (3.2) become 1. Thus (3.2) is equivalent to $\sum_{\alpha \in \mathbb{Z}} g_0(\cdot - \alpha) = 0$. In particular, if $\sum_{\alpha \in \mathbb{Z}} g(\cdot - \alpha) = 0$ and $\sum_{\alpha \in \mathbb{Z}} \phi_0(\cdot - \alpha) = 0$ hold, then (3.2) is valid. Hence, the corresponding cascade algorithm converges. \square

Example 3.3. Consider the nonhomogeneous vector refinement equation

$$\phi(x) = g(x) + \sum_{j=0}^2 a(j)\phi(2x - j), \quad x \in \mathbb{R},$$

where $g = (g_1, g_2)^T$ is a 2×1 vector of compactly supported functions in $L_2(\mathbb{R})$, and

$$a(0) = \begin{bmatrix} 1/2 & 1/2 \\ 1/4 & 1/4 \end{bmatrix}, \quad a(1) = \begin{bmatrix} 1 & 0 \\ 0 & 1/2 \end{bmatrix}, \quad a(2) = \begin{bmatrix} 1/2 & -1/2 \\ -1/4 & 1/4 \end{bmatrix}.$$

Let $\phi_0 = (\phi_{0,1}, \phi_{0,2})^T$ be a 2×1 vector of compactly supported functions in $L_2(\mathbb{R})$. Then the cascade algorithm associated with a, g , and ϕ_0 is L_2 -convergent, provided

$$(3.5) \quad \sum_{\alpha \in \mathbb{Z}} g_1(\cdot - \alpha) = 0 \quad \text{and} \quad \sum_{\alpha \in \mathbb{Z}} \phi_{0,1}(\cdot - \alpha) = 1.$$

In order to justify our claim, we first compute the sequence b as given in (2.6). We have $b(\alpha) = 0$ for $\alpha \in \mathbb{Z} \setminus [-2, 2]$, and

$$b(-2) = [a(2) \otimes a(0)]/2, \quad b(-1) = [a(1) \otimes a(0) + a(2) \otimes a(1)]/2,$$

$$b(0) = [a(0) \otimes a(0) + a(1) \otimes a(1) + a(2) \otimes a(2)]/2,$$

$$b(1) = [a(0) \otimes a(1) + a(1) \otimes a(2)]/2, \quad b(2) = [a(0) \otimes a(2)]/2.$$

Let B be the block matrix $(b(2\alpha - \beta))_{-2 \leq \alpha, \beta \leq 2}$. By a straightforward computation we find that 1 is a simple eigenvalue of the matrix B and the other eigenvalues of B are less than 1 in modulus. Note that 2 is a simple eigenvalue of the matrix $\sum_{\alpha \in \mathbb{Z}^2} a(\alpha)$ with $(1, 0)$ being a left eigenvector. Further, one can check

$$(1, 0) \sum_{j=0}^2 a(2j + i) = (1, 0), \quad i = 0, 1.$$

Thus the cascade algorithm associated with the homogeneous refinement equation with mask a converges in the L_2 -norm (see [22] and [16]). Hence, by Corollary 2.6 and Remark 2.7, the cascade algorithm associated with a, g , and ϕ_0 converges provided the conditions in (3.5) are satisfied. \square

Example 3.4. Consider the nonhomogeneous vector refinement equation

$$(3.6) \quad \phi(x) = A\phi(2x) + g(x), \quad x \in \mathbb{R}^2,$$

where A is a nonzero 2×2 matrix and $g = (g_1, g_2)^T$ is a 2×1 vector of compactly supported functions in $L_2(\mathbb{R}^2)$. Let $\phi_0 = (\phi_{0,1}, \phi_{0,2})^T$ be a 2×1 vector of compactly supported functions in $L_2(\mathbb{R}^2)$. The corresponding cascade algorithm is given by $\phi_k = A\phi_{k-1}(2\cdot) + g, k = 1, 2, \dots$. Let $g_0 := g + Q_a\phi_0 - \phi_0$ and $v(\alpha) := \text{vec}(g_0 \odot g_0^T)(\alpha), \alpha \in \mathbb{Z}^2$. We observe that $v(0) = 0$ if and only if $g_0 = 0$.

In this case, $a(0) = A$ and $a(\alpha) = 0$ for $\alpha \in \mathbb{Z}^2 \setminus \{0\}$. Let b be the sequence given in (2.6). Then

$$b(0) = \bar{A} \otimes A/4 \quad \text{and} \quad b(\alpha) = 0 \quad \forall \alpha \in \mathbb{Z}^2 \setminus \{0\}.$$

Note that $\rho(\bar{A} \otimes A) = \rho(A)^2$. For sufficiently large k , we have

$$T_b^k v(0) = (\bar{A} \otimes A/4)v(0) \quad \text{and} \quad T_b^k v(\alpha) = 0 \quad \forall \alpha \in \mathbb{Z}^2 \setminus \{0\}.$$

Thus, if $\rho(A) < 2$, then $\rho(T_b) < 1$ and the cascade algorithm associated with A , g , and any ϕ_0 is L_2 -convergent, by Theorem 2.4.

Let λ_1, λ_2 be the two eigenvalues of A . Then the eigenvalues of the matrix $\bar{A} \otimes A$ are $|\lambda_1|^2, \lambda_1 \bar{\lambda}_2, \lambda_2 \bar{\lambda}_1$, and $|\lambda_2|^2$. If $|\lambda_1| \geq 2$ and $|\lambda_2| \geq 2$, then the cascade algorithm associated with A , g , and ϕ_0 is L_2 -convergent only if $g_0 = 0$, *i.e.*, ϕ_0 is the solution of the refinement equation (3.6).

It remains to deal with the case $|\lambda_2| < 2 \leq |\lambda_1|$. After a suitable coordinate change we may assume that A has the following form $A = \text{diag}(\lambda_1, \lambda_2)$. Then the cascade algorithm associated with A , g , and ϕ_0 is L_2 -convergent if and only if $\phi_{0,1}$ is the L_2 -solution of the equation $\varphi = \lambda_1 \varphi(2 \cdot) + g_1$.

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