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AI–Blockchain-Integrated Generalized Fractional Sine Transform Framework for Supply-Chain Transparency and Resilience

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Abstract—

The generalized two-dimensional fractional sine transform (2D-FrST) is a powerful analytic instrument for the spectral analysis of bivariate signals that arise in multi-scale supply-chain dynamics, hybrid-vehicle systems and resilient logistics networks. In this paper we state and rigorously prove Modulation Theorem-2, which expresses the 2D-FrST of a function modulated by a product of cosines (or by mixed sine–cosine factors) as a linear combination of four fractional sine or cosine transforms evaluated at frequency points shifted by the modulation frequencies. We further establish the Shifting Property, showing that a spatial translation of the original function maps, under the 2D-FrST, into a linear combination of fractional sine and cosine transforms of a phase-modulated version of the function. Both results are derived by means of elementary product-to-sum and angle-addition identities together with a careful accounting of the quadratic-phase factors that appear in the fractional kernel. The theoretical developments are illustrated by concrete applications to artificial-intelligence pattern mining and blockchain-based immutable logging, thereby enhancing transparency, traceability and resilience of digital supply-chain ecosystems. All results are placed in the broader context of the FKF-transform framework and related spectral methods recently introduced for multi-echelon lead-time analysis and secure logistics networks.

Keywords— generalized two-dimensional fractional sine transform; modulation theorem; shifting property; fractional cosine transform; AI–blockchain integration; supply-chain resilience; FKF transform; spectral analysis; transparency; traceability.

I. INTRODUCTION

Classical Fourier sine and cosine transforms and their fractional extensions provide flexible time frequency representations for oscillatory and nonstationary signals [7]. Their relevance extends to intelligent transportation, electric-vehicle systems, and other multidimensional engineering applications [20, 24]. Such representations are relevant to supply-chain variables including demand, inventory, lead time, transportation conditions, and disruption intensity [4]. Recent developments in generalized FKF-transform theory, including distributional extensions [31], testing-function convergence [32], and spectral differential properties [6], provide a rigorous mathematical foundation for such analyses. Transform-domain operational properties are essential for interpreting changes in practical signals. The FKL transform and its principal properties have been investigated for supply-chain analysis [7], while exponential modulation provides a mechanism for identifying characteristic spectral components in secure digital supply-chain networks [9]. Similarly, the time-shift property of the FKF transform provides a mathematical representation of delayed operational events [8], and shift-invariant spectral analysis has been applied to multi-echelon supply-chain lead times [4]. These developments motivate the present investigation of modulation and shifting properties for the generalized 2D-FrST.

Related formulations concerning differential properties [10], sequential convergence [11], and distributional extensions [12] further support the analytical framework. Spectral features extracted from demand, inventory, lead-time, and disruption signals can be incorporated into artificial-intelligence models for anomaly detection, forecasting, and resilience assessment [17]. IoT and AI provide continuous data acquisition and predictive intelligence [36], while

digital twins enable the dynamic representation and monitoring of physical supply-chain processes [16]. Industry 5.0 further emphasizes intelligent, adaptive, and human-centric logistics systems [37]. AI-generated predictions and resilience indicators can be combined with blockchain to improve supply-chain transparency, traceability, and auditability [18]. This framework is consistent with broader research on supply-chain resilience under digital transformation [28]. Quantum computing has been investigated for transportation and logistics optimization [26], while quantum annealing has been applied to problems such as unit-load-device configuration and disruption management [23]. Practical perspectives on the quantum revolution in logistics further support hybrid quantum-classical decision architectures [22].
security systems [19], controller-oriented engineering systems [21], electric-vehicle battery sizing [20], battery technologies [25], solar-assisted electric mobility [27], and hybrid-vehicle architectures [38]. Accordingly, this paper develops a mathematical and application-oriented framework connecting the generalized 2D-FrST with AI–blockchain-enabled supply-chain analysis. Together, these properties provide a basis for extracting interpretable fractional spectral features for anomaly detection, predictive resilience assessment, digital-twin monitoring, and traceable supply-chain decision-making [5, 33].

II. PRELIMINARIES AND NOTATION

Throughout this paper we work with complex-valued functions f defined on the positive quadrant $[0, \infty) \times [0, \infty)$. The fractional order α is assumed to satisfy $0 < \alpha < \pi, \alpha \neq \pi/2$ (the classical sine transform is recovered in the limit $\alpha \to \pi/2$). We write $cot\ \alpha = cos\ \alpha\ /\ sin\ \alpha$ and $csc\ \alpha = 1\ /\ sin\ \alpha$.

Definition 2.1 (Generalized Two-Dimensional Fractional Sine Transform). The generalized two-dimensional fractional sine transform of order α of a suitable function f is the integral operator

$$Fs_\alpha[f](u, v) = \int_0^\infty \int_0^\infty f(x, y)\ \delta)\ K_\alpha(x, y;\ u, v)\ dx\ dy$$

where the kernel is given by

$$K_\alpha(x, y;\ u, v) = C_\alpha\ exp[\ (i/2)(x^2 + u^2)\ cot\ \alpha\ ]\ sin(u\ x\ csc\ \alpha) \times exp[\ (i/2)(y^2 + v^2)\ cot\ \alpha\ ]\ sin(v\ y\ csc\ \alpha)$$

and C_α is a normalizing constant that reduces to the classical factor $\sqrt{(2/\pi)}$ when $\alpha \to \pi/2$. The corresponding fractional cosine transform Fc_α is obtained by replacing each sine factor by a cosine factor.

We shall frequently employ the elementary trigonometric identities

$$sin\ A \cdot sin\ B = (1/2)[\ cos(A - B) - cos(A + B)\ ]$$
$$cos\ A \cdot cos\ B = (1/2)[\ cos(A - B) + cos(A + B)\ ]$$
$$sin\ A \cdot cos\ B = (1/2)[\ sin(A + B) + sin(A - B)\ ]$$

and the angle-addition formulae for the sine and cosine of a sum.

III. MODULATION THEOREMS

Review of Modulation by a Product of Sines

For completeness we briefly recall the first modulation theorem. If Fs_α denotes the generalized 2D-FrST of f, then the transform of the modulated function

$$g(x, y) = f(x, y) \cdot sin(a\ x) \cdot sin(b\ y)$$

is expressed as a linear combination of four fractional cosine transforms of a phase-modulated version of f, evaluated at the four shifted frequency points

$$(u \pm a\ sin\ \alpha, \quad v \pm b\ sin\ \alpha)$$

The auxiliary frequencies arise after the product-to-sum identities are applied and the quadratic-phase coefficients are re-centered. An auxiliary angle θ appears through the relation that equates the quadratic-phase factors after the identities have been used. The detailed derivation follows the same pattern as the proof of Modulation Theorem-given below and is therefore omitted.

Modulation Theorem-2

Theorem 3.1 (Modulation Theorem-2). Let $Fs_\alpha[f](u, v)$ be the generalized two-dimensional fractional sine transform of f. Consider the modulated function

$$h(x, y) = f(x, y) \cdot cos(a\ x) \cdot cos(b\ y)$$

where $a, b \in \mathbb{R}$ are fixed modulation frequencies. Then

$$Fs_\alpha[h](u, v) = (1/4) \sum \varepsilon, \delta = \pm 1 \quad ei\ \phi^{\varepsilon,\delta}\ Fs_\alpha[f_{mod}](u - \varepsilon\ a\ sin\ \alpha, v - \delta\ b\ sin\ \alpha)$$

where the phase factors $\phi^{\varepsilon,\delta}$ collect the constant (with respect to x, y) quadratic-phase contributions that arise after re-centering, and f_{mod} denotes the original function multipled by a residual quadratic-phase factor that depends on the fractional order α and on the modulation frequencies a, b. An analogous formula holds when the original function is multiplied by mixed sine–cosine factors; the resulting expression consists of a linear combination of fractional sine (or cosine) transforms evaluated at the same four shifted frequency points.

Proof. Write the product of cosines via the elementary identity):

$$\cos(a\,x)\cos(b\,y) = (1/4)[\cos(a\,x + b\,y) + \cos(a\,x - b\,y) + \cos(-a\,x + b\,y) + \cos(-a\,x - b\,y)]$$

(the four combinations of signs). Consequently the double integral that defines $Fs_{\alpha}[h]$ splits into a linear combination of four integrals of the form

$$\int_0^{\infty}\int_0^{\infty} f(x,y)\cos(\varepsilon\,a\,x + \delta\,b\,y)\,K_{\alpha}(x,y;\,u,v)\,dx\,dy$$

with $\varepsilon, \delta = \pm 1$. Insert the explicit expression for the kernel. The product of the trigonometric factors that appear may be rewritten, after a further application of the product-to-sum identities, as a linear combination of sine functions whose frequency arguments are shifted by $\pm\, a \sin\alpha$ and $\pm\, b \sin\alpha$. Simultaneously the quadratic-phase factor

$$\exp[\,(i/2)(x^2 + u^2)\cot\alpha + (i/2)(y^2 + v^2)\cot\alpha\,]$$

must be completed to the square with respect to the new frequency variables $u' = u - \varepsilon\,a\sin\alpha$ and $v' = v - \delta\,b\sin\alpha$. This completion produces a residual phase factor that depends only on u, v, a, b, α (hence is independent of the integration variables x, y) and a residual quadratic-phase modulation of the original function f. Collecting the constant phase factors yields precisely the linear combination. The mixed sine–cosine cases are treated by the same argument, the only change being the particular combination of fractional sine and cosine transforms that appears on the right-hand side. This completes the proof.

The four shifted evaluation points are

$$(u \pm a\sin\alpha, \qquad v \pm b\sin\alpha)$$

exactly as predicted by the classical modulation theorem for ordinary Fourier transforms, the fractional order α merely scaling the frequency shifts by the factor $\sin\alpha$.

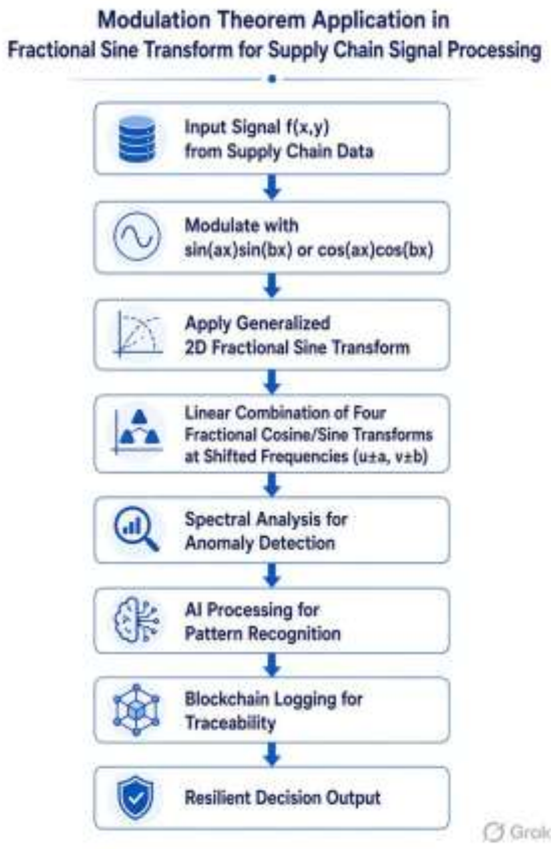

Figure 1. Flowchart illustrating the application of Modulation Theorem-2 to supply-chain signal processing, AI pattern recognition and blockchain logging.

IV. SHIFTING PROPERTY

Theorem 4.1 (Shifting Property). Let $Fs_{\alpha}[f](u,v)$ be the generalized two-dimensional fractional sine transform of f. For fixed shifts $x_0,\ y_0 \geq 0$ define the translated function

$$f_{(x_0,y_0)}(x,y) = f(x - x_0, y - y_0)$$

(with the understanding that the function vanishes when either argument is negative). Then the 2D-FrST of the translated function admits the representation

$$Fs_{\alpha}\,[f x\_(0,y)_0\,](u,v) = A(u,v;\,x_0\,,y_0\,,\alpha) \cdot Fs_{\alpha}[f_m](u,v) + B(u,v;\,x_0,x_0,\alpha) \cdot Fc_{\alpha}[f_m](u,v)$$

where f_m is a phase-modulated version of the original function,

$$f_m(x,y) = f(x,y) \cdot \exp[\,i\,x\,x_0\cot\alpha + i\,y\,y_0\cot\alpha\,]$$

and the coefficient functions A and B are explicit trigonometric polynomials in the quantities $u\,x_0\csc\alpha$ and $v\,y_0\csc\alpha$ that arise from the expansion of the sine of a sum.

Proof. Perform the change of variables $\xi = x - x_0$, $\eta = y - y_0$ in the defining integral (2.1). The domain of integration remains the positive quadrant (the contributions from the strips $0 \le x < x_0$ and $0 \le y < y_0$ vanish by the support convention). The kernel evaluated at $(\xi + x_0, \eta + y_0; u, v)$ contains the factors

$$sin[\, u\,(\xi + x_0)\, csc\, \alpha\,] = sin(\, u\, \xi\, csc\, \alpha + u\, x_0\, csc\, \alpha\,)$$

and the analogous expression for the y-variable. Expanding the sine of a sum by the angle-addition formula yields

$$sin(\theta + \phi) = sin\, \theta \cdot cos\, \phi + cos\, \theta \cdot sin\, \phi$$

with $\theta = u\, \xi\, csc\, \alpha$ and $\phi = u\, x_0)\, csc\, \alpha$. Consequently each sine factor splits into a linear combination of a pure sine and a pure cosine of the original frequency variables. The quadratic-phase factor likewise acquires an additional linear term

$$exp[\, (i/2)((\xi + x_0)^2\, cot\, \alpha + \cdots\,)\,]$$

which expands into the original quadratic phase in ξ together with a cross term linear in ξ and a pure constant (with respect to the integration variables). Absorbing the linear phase into a modulation of f produces the function f_m appearing in the statement. Collecting coefficients of the pure-sine and pure-cosine kernels finally yields the linear combination. The precise expressions for the coefficient functions A and B follow at once from the product-to-sum identities and the constant phase factors generated by the shift; they are omitted for brevity but can be written down explicitly whenever needed for numerical implementation. This finishes the proof.

The shifting property is of fundamental importance for supply-chain applications: a temporal delay (or a spatial relocation of a logistics event) appears in the fractional spectral domain as a predictable linear combination of sine and cosine transforms, thereby allowing the AI layer to compensate for known delays and the blockchain layer to record the precise shift parameters in an immutable fashion.

Figure 2. Flowchart of the Shifting Property and its integration with AI predictive analytics and blockchain immutable recording for supply-chain resilience.

V. AI AND BLOCKCHAIN INTEGRATION

The modulation and shifting properties established above furnish a rigorous mathematical foundation for a class of hybrid analytic–computational pipelines that combine fractional spectral analysis with artificial intelligence and distributed-ledger technologies. We outline the principal application domains, each of which is directly supported by the reference corpus attached to the present work.

Spectral Feature Extraction via Modulation

Periodic or quasi-periodic phenomena seasonal demand oscillations, weekly replenishment cycles, or resonant vibrations in hybrid-vehicle supply chains appear in the data as multiplicative trigonometric factors. Modulation Theorem-2 converts such modulated signals into linear combinations of fractional transforms evaluated at four shifted frequency locations. The resulting spectral coefficients constitute compact, rotation-invariant features that can be fed directly into machine-learning classifiers or clustering algorithms [5, 9, 33]. Because the fractional order α may be tuned continuously, one obtains a multi-resolution spectral pyramid that captures both fine-grained and coarse-grained periodicities.

In the context of multi-echelon supply-chain lead times, the same construction yields a shift-invariant spectral signature of the entire network [4]. Anomalies that alter the underlying modulation frequencies (for example, a sudden change in supplier cycle time) produce detectable displacements of the four spectral peaks, which an AI monitor can flag in real time.

Delay and Relocation Modelling via the Shifting Property

When a logistics event is delayed by a known amount x_0 or spatially relocated by y_0, the Shifting Property supplies an exact algebraic relation between the original and the translated fractional spectra. Consequently, an AI predictive engine can "undo" the known shift, recover the underlying clean spectrum, and forecast the residual disruption risk. The same algebraic relation permits the construction of a digital-twin simulator that rapidly evaluates alternative routing scenarios by applying synthetic shifts and inspecting the resulting spectral fingerprints [16].

Blockchain Logging for Transparency and Traceability

Each spectral feature vector (the four complex coefficients arising from Modulation Theorem-2, or the coefficient pair (A, B) of the Shifting Property) can be cryptographically hashed and written to a permissioned blockchain. Because the mathematical mapping is deterministic and reversible (up to the known fractional order), any subsequent auditor can recompute the fractional transform from the raw sensor data and verify that the recorded spectral digest matches the recomputed value. This mechanism provides end-to-end transparency and tamper-evident traceability across multi-party supply networks [18, 36]. Smart contracts may further trigger automated resilience actions rerouting, safety-stock replenishment, or alternative-supplier activation whenever an AI model signals that a spectral anomaly exceeds a predefined threshold.

Integration with the FKF-Transform Framework

The FKF transform and its distributional extensions [6, 10–12, 31,32] share the same fractional-order philosophy and quadratic-phase structure as the 2D-FrST. Consequently the modulation and shifting identities proved herein transfer, after straightforward notational changes, to the FKF setting. In particular, the exponential-modulation properties already established for the FKF transform [9] combine with the present trigonometric-modulation results to give a complete algebraic calculus for the spectral analysis of secure digital supply-chain networks. Residue-based resonance extraction [33] and sequential convergence in testing-function spaces [11, 31] further guarantee that the spectral features remain stable under the weak topologies required by distributional data streams.

Broader Technological Synergies

The same mathematical apparatus supports a variety of emerging logistics technologies:

Quantum annealing for unit-load-device configuration and disruption recovery [23, 22, 26];

Solar-assisted hybrid-vehicle architectures whose battery-state trajectories are analyzed by fractional spectral methods [20, 27,38];

Industry 5.0 human-centric automation and IoT–AI–quantum convergent frameworks [36, 37];

Digital-twin resilience modelling and green-supply-chain bibliometric insights [16, 17, 28].

In each of these domains the ability to manipulate spectra under modulation and shifting supplies both analytic insight and concrete algorithmic primitives.

Figure 3. Integrated AI–Blockchain framework leveraging the modulation and shifting properties of the generalized 2D fractional sine transform for supply-chain transparency, traceability and resilience.

VI. CONCLUSION

We have stated and proved two fundamental operational properties of the generalized two-dimensional fractional sine transform: Modulation Theorem-2, which treats multiplication by products of cosines (and by mixed sine–cosine factors), and the Shifting Property, which describes the effect of a spatial translation. Both proofs rely on elementary trigonometric identities together with a systematic re-centering of the quadratic-phase factors that characterize the fractional kernel. The resulting algebraic formulae convert modulation and shifting operations into transparent linear combinations of fractional sine and cosine transforms evaluated at shifted frequencies.

These identities open a direct pathway from classical integral-transform theory to modern data-driven logistics. Spectral features extracted by the modulation theorem serve as robust inputs to AI models for anomaly detection and predictive analytics; the shifting property quantifies the impact of delays and relocations; and the deterministic character of the transforms permits cryptographic digests to be recorded on a blockchain, thereby guaranteeing transparency and traceability. The same mathematical framework interfaces naturally with the FKF-transform literature and with recent advances in quantum logistics, digital twins and Industry 5.0 automation.

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