Dirac-Comb Convolution Detector [Grid]

Digital Twin Specification

Twin Code:	DF-CONV01
Twin Name:	Dirac-Comb Convolution Detector [Grid]
Category:	Detector
Type:	Function-Based
Version:	1.0
Package:	Platform
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Description

Modeling complex sources such as extended, partially coherent, or multi-emitter sources often requires superimposing many laterally shifted modes. Propagating each mode separately through an optical system is computationally expensive. This detector twin provides a powerful alternative: instead of propagating all modes, you propagate only the central mode. The detector then performs a convolution with a rectangular Dirac-comb grid, which is mathematically equivalent to superimposing many laterally shifted copies of the propagated field, provided the optical system is laterally invariant. This technique dramatically reduces simulation time while accurately representing sources like rectangular extended sources, LED arrays, or multi-mode fiber outputs.

Measured Quantity

The detector outputs the convolved field or derived quantity (depending on the position of the add-on in the detector channel), typically:

- **Electromagnetic field**: When placed after the "Electromagnetic Field Quantities" add-on (coherent superposition).
- **Irradiance**: When placed after the "Irradiance" add-on (incoherent superposition).

The result represents the superposition of all laterally shifted source copies.

Model Parameters

The Dirac-Comb Convolution Detector itself has no configurable parameters. Its behavior is controlled exclusively through its associated **Convolution with Delta Grid** add-on:

- **Show Grid**: Toggle to visualize the Dirac-comb grid as an output overlay (helpful for verification).
- **Number of Modes**: Specifies the number of Dirac delta functions in the convolution grid for the x- and y-directions (e.g., $N_x \times N_y$). This determines how many laterally shifted copies are superimposed.
- **Chip Size**: Defines the total lateral extent of the Dirac-comb grid (e.g., $L_x \times L_y$). Together with the Number of Modes, this fixes the spacing between individual delta functions: $\Delta x = L_x/(N_x - 1)$, $\Delta y = L_y/(N_y - 1)$.
- **Weight Distribution (optional)**: A 2D data array that assigns different weights to each shifted copy. This can model, for example, the intensity profile of an extended source. The array must have the same sampling dimensions as the detector add-on ($N_x \times N_y$).

Simulation Model

The fundamental principle is based on the convolution theorem. For a laterally invariant system, propagating a field $U(\boldsymbol{\rho})$ through the system (operator $\mathcal{S}$) and then convolving with a Dirac comb $\text{Ш}(\boldsymbol{\rho})$ is equivalent to first convolving the input field with the Dirac comb and then propagating through the system:

$$\mathcal{S}\big[U(\boldsymbol{\rho})\big] * \text{Ш}(\boldsymbol{\rho}) = \mathcal{S}\big[U(\boldsymbol{\rho}) * \text{Ш}(\boldsymbol{\rho})\big]. \tag{1}$$

However, in this detector, we exploit the reverse: we propagate only the central field $U(\boldsymbol{\rho})$ through the system (saving computation time) and then perform the convolution with the Dirac comb on the detector side. For a rectangular Dirac-comb grid with positions $\boldsymbol{\rho}_{mn} = (m\Delta x, n\Delta y)$, the output field $U_{\text{out}}(\boldsymbol{\rho})$ is given by:

$$U_{\text{out}}(\boldsymbol{\rho}) = \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} w_{mn}\, U_{\text{prop}}(\boldsymbol{\rho} - \boldsymbol{\rho}_{mn}), \tag{2}$$

where:

- $U_{\text{prop}}(\boldsymbol{\rho})$ is the propagated field from the central source mode,
- w_{mn} are the optional weight coefficients,
- N_x, N_y are the Number of Modes in x and y,
- $\Delta x, \Delta y$ are the spacings derived from Chip Size and Number of Modes.

Key Physical Principle: Lateral Invariance

This technique is valid only when the optical system is **laterally invariant**meaning its impulse response is shift-invariant. This holds for many systems consisting of lenses, free-space propagation, and apertures, provided there are no laterally varying elements (e.g., gratings with position-dependent periods, tilted components). When this condition is met, the superposition in Eq. (2) accurately represents the full multi-mode simulation.

Typical Application Scenarios

1. **Rectangular Extended Sources**: Model an LED chip or a laser diode bar with a rectangular emitting area. Use the Chip Size to match the source dimensions and the Number of Modes to achieve the desired spatial sampling of the emission profile.

2. **LED Arrays and Multi-Emitter Sources**: Simulate a 2D array of VCSELs or micro-LEDs by choosing Number of Modes matching the array size and Chip Size matching the overall array footprint. Optionally, use the Weight Distribution to account for intensity variations across the array.

3. **Multi-Mode Fiber Outputs**: Approximate the output of a multi-mode fiber as a superposition of laterally shifted coherent modes (or incoherent modes, depending on add-on placement). The Chip Size corresponds to the fiber core diameter.

4. **Partially Coherent Illumination in Imaging Systems**: Model Köhler illumination or other partially coherent schemes by treating the source as an incoherent superposition of mutually incoherent point sources. Place the convolution add-on after the Irradiance add-on for incoherent superposition.

5. **Laser Beam Homogenizers**: Simulate the effect of a fly's eye homogenizer or a diffractive beam shaper by representing the input as a grid of beamlets (coherent or incoherent) and observing their superposition at the target plane.

6. **Scanning Systems**: Model a scanning laser beam by using a moving Dirac comb (with appropriate weights) to represent the beam's positions over time, then analyze the integrated effect on a detector.

Software Usage

1. **Adding the Detector**: From the Digital Twin Hub, add the "Dirac-Comb Convolution Detector [Grid]" (DF-CONV01) to your optical system. Position it at the plane where you want to observe the superimposed field.

2. **Configuring the Detector Channel**: Open the detector's properties and navigate to the Add-ons tab. Add and configure the **Convolution with Delta Grid** add-on:
   - Set "Number of Modes" (e.g., 5×5 for a 5×5 grid).
   - Set "Chip Size" (e.g., $1\,\text{mm} \times 1\,\text{mm}$).
   - (Optional) Load or define a "Weight Distribution" 2D data array.
   - Enable "Show Grid" for visualization.

3. **Choosing Coherent or Incoherent Superposition**: The position of the add-on in the channel determines the type of superposition:
   - **Incoherent superposition** (e.g., for LEDs or thermal sources): Place the "Convolution with Delta Grid" add-on **after** the "Irradiance" add-on. The detector will first compute irradiance from the propagated field, then convolve it with the Dirac comb (adding intensities).
   - **Coherent superposition** (e.g., for laser arrays or coherent imaging): Place the "Convolution with Delta Grid" add-on **directly after** the "Electromagnetic Field Quantities" add-on. The detector will convolve the complex electromagnetic field with the Dirac comb, preserving phase information and allowing interference between the shifted copies.

4. **Running the Simulation**: Execute the field tracing. Only the central mode is propagated through the system; the convolution is applied numerically within the detector.

5. **Interpreting Results**:
   - If "Show Grid" was enabled, you will see an overlay indicating the Dirac-comb grid positions.
   - The resulting field/irradiance distribution shows the superposition of all shifted copies.
   - Use the detector's data export to analyze the combined profile.

6. **Verification**: For simple systems (e.g., free-space propagation only), you can verify the result by manually propagating multiple shifted sources and comparing with the detector's output.

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Related Twins:	DF-CONV02, CF-DCMP01, SB-SMUL01