Spatial information transmission using axial
temporal coherence coding

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We present an approach that can be used for transmission of information through space-limited systems or for superresolution. The spatial information is coded with different axial temporal coherence by interfering every spatial region in the input with the same region, but with a certain known delay in the longitudinal axis. Every spatial region has different delay. After mixing all of the spatial information, it is transmitted through the space-limited system. At the detection the information is passed through a similar interference setup containing certain axial delay. By temporally scanning along the longitudinal axis, each time a different spatial region that was coded with the corresponding axial delay is reconstructed. To allow coding of different spatial regions with different and small axial delays, we use a thermal light source that has very short coherence length. We include experimental validation of the presented approach. © 2007 Optical Society of America

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The Rayleigh diffraction limit gives the maximum density of spatial information that can be transmitted through an optical system. Together with the field of view, it defines the space-bandwidth product of the system that determines the amount of information that can be handled by a system. Nevertheless, this limit can be circumvented by coding additional information on unused degrees of freedom of the system. A typical application of this concept is in superresolution, whose aim is to pass the spatially high-resolution information throughout a space-limited system. It can be achieved by producing a synthetically large aperture by coding the spatial features into different domains such as time, polarization, or wavelength. It is worth noting that the information capacity increase is the relevant issue in super-resolution application and can alternatively be achieved by a field-of-view increase keeping the system resolution constant. This corresponds to an exchange between spatial and spatial-frequencies spaces. Field of view and resolution (as given by the cutoff frequency of the system) are dual quantities in these spaces.

Recently a new technique that uses orthogonal mutual coherence coding was proposed. This technique is based on illuminating the object with orthogonal coding of the mutual intensity function (MIF). By using the fact that the MIF can be synthesized, displayed, and optically processed, an optical coding system that overcomes the diffraction limit was demonstrated. Based on the fact that spatial information coding can be implemented using orthogonal mutual coherence coding, we suggest an alternative approach of using temporal coherence coding, i.e., instead of generating a transversally different coherence distribution, we use the longitudinal axis to code the transversal spatial information. By applying different axial coherence to different spatial pixels of the object, we can fold a two-dimensional image into a smaller spatial domain (a single pixel, in the limit case) and then transmit it through the space-limited system. The decoding setup will be similar to the encoding one.

The suggested concept is as follows: an optical setup produces a light beam with the desired self-coherence function (SCF). This beam illuminates the input object. The illuminating beam consists of a sum of a reference beam and the same beam passed through a spatial mask having different time delays in different spatial regions. The illumination is orthogonal; i.e., there are no two spatial regions having the same time delay. After transmitting the coded information through the space-limited imaging system, the image is recovered using an optical decoding system that is identical to the coding one. In the decoding, the multiplexed spatial information is separated and the image is reconstructed by separating the various SCFs that coded the spatial content of the object. The decoding recovers the information after time averaging. However, since the temporal fluctuations of the phases are at the speed of light, the averaging time can be as short as a few times the illumination coherence time (which could be as low as femtoseconds).

The SCF is defined as described in Ref. 14:

\[ |\Gamma_{11}(\tau)| = \langle u(P,t + \tau)u^*(P,t) \rangle, \]  

(1)

where \( u(P,t) \) is an input complex amplitude, \( P \) represents the spatial coordinates, \( t \) is the time axis, and \( \tau \)
is the time difference between the points. \( \langle \rangle \) describes ensemble averaging over time. For an incoherent field \( |\Gamma_{11}(\tau)| = 0 \) for all \( \tau \neq 0 \). The coding system is based on the possibility that every spatial region can have autocorrelation with a unique time delay that will separate this specific spatial region from the others. The recovery of every region will be based on the time delay that was used for its coding. The incoherent light used in the coding system can be described by the temporal phase decorrelation after a time that is longer than the coherence time \( \tau_c \). The coherence time has a value that is of the same order of magnitude as \( 1/\Delta v \), where \( \Delta v \) is the spectral bandwidth of the illuminating source. We use broadband spectrum illumination to have short \( \tau_c \). Proper coding will generate a SCF \( \Gamma_{11}(\pi(P)) = \langle u(P_1, t + \pi(P))u^*(P_1, t) \rangle \) that in the decoding will yield \( |\Gamma_{11}(\pi(P))| = 0 \) for all \( \pi(P) \), except when \( \pi(P) = \pi(P_1) \), where it has a finite value.

In the experimental validation, we demonstrate a reduction in the spatial extent to be transmitted by the system, by the use of the proposed coherence coding, by a factor of 2. We have constructed the experimental schematic setup as depicted in Fig. 1(a). The picture of the encoding part is seen in Fig. 1(b). The complete setup consists of two Michelson interferometers, one for the coding and the second for decoding. After the coding and before the decoding, we have spatial compression of the information to simulate its transmission through a space-limited system, such as a conventional imaging system or a fiber bundle.

The first interferometer was built from two branches with the same length. One branch has an addition of thin glass that time shifts half of the image by \( \tau_c \) from the second half. A thicker glass holds the delay plate, and a similar one is used in the other branch for compensation [Fig. 1(b)]. Afterward the image is compressed, superimposing the two halves of the image, one on top of the other. The second interferometer (the decoding part) is made initially with two equal length branches, where in one of the branches the length can be varied. The length variation controls the time delay \( \tau_c \), enabling us to recover the specific region with the same coding time. Mathematically, assuming the time delay of the \( \tau_c \), coded image of spatial region \( P_1 \) and the \( \tau_c \), coded spatial region of \( P_2 \), when we tune the decoding setup for the proper time delay of \( \tau_c \) or \( \tau_c \), we have extracted the corresponding spatial region:

\[
|\Gamma_{11}(\tau_c)| = \langle u(P_1, t + u(P_2, t + \tau_c)) \rangle = \langle u(P_1, t + u(P_2, t + \tau_c)) \rangle,
\]

\[
|\Gamma_{11}(\tau_c)| = \langle u(P_1, t + u(P_2, t + \tau_c)) \rangle = \langle u(P_1, t + u(P_2, t + \tau_c)) \rangle.
\]
ments are not large. For instance, a 5 mask would increase the information capacity by a factor of 25.

After the spatial compression, A was superimposed on B. Decoding by SCF is implemented in the second interferometer. Both systems were implemented using simple lenses (singlets), which provide enough resolution and field of view for the target with the double spatial content. In a real application, this approach for real world scenes.

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