Abstract

Our research program is concerned with the development of an information theory of classical electromagnetic fields, with applications to wireless communications, remote sensing, and radar. In the present work, emphasis is given to the derivation of upper bounds for the Shannon information capacity of a wireless communication channel formed by a rather general receiving antenna and a transmitting antenna whose support is assumed to be contained within a mathematical spherical volume of given radius. Due to reciprocity, the upper bound results also apply as fundamental bounds for the information capacity of a wave sensor of a given size, be it an antenna, the eye, or any wavefield-measuring device. This work includes numerical results illustrating the derived theory. A discussion of applications of the derived theory and numerical results to wavefield imaging is presented, in addition to the concept of degrees of freedom of the data, and classes of recoverable object profiles, using near or far electromagnetic fields, in other imaging systems and it also clarifies the possibility of super-resolution in certain situations. More generally, the developments are derived from the first principles of physics, provided by the classical electromagnetic field framework and are therefore fundamental for both analysis and design of a variety of wireless communication, remote sensing and radar systems.

State of the Art

- Miller [2], [3] studied the orthogonal communication channels between two arbitrary volumes in free space radiating a scalar waves and, in a later generalization, [4] for volumes radiating electromagnetic waves.
- The scalar version of Miller’s work was later extended by Hanlen and Fu [5] to include the effect of scatterers in the propagation path.
- Gustafsson and Nordebo [6] analyzed the fundamental limitations in the capacity of an arbitrary electromagnetic antenna under Rayleigh fading channel and white Gaussian noise, obtaining into account antenna theory and broadband matching.
- Poon et al. [7] derived expressions for the NDF of a communication system with different array geometries and with a channel model based on measurements, providing upper bounds and lower bounds.
- Challenges and Significance

In this work, we present the initial steps in using Shannon’s information theory to characterize the fundamental limits in the information transfer of a given device size under various physical constraints.

- In addition to the obvious applications in communication systems, the information theoretical concept used in this work is important in other applications like remote sensing where, for instance, we can characterize the performance of imaging systems in terms of the amount of information about the object contained in the image rather than how much the image resembles the object. Important challenges include the consideration of systematic as well as appropriate constraints.

Technical Approach

- Singular Value Decomposition (SVD)

\[ \mathbf{A} \mathbf{X} = \mathbf{Y} \]

Define:

\[ P = \sum_{i=1}^{n} S_i^2 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

SVD:

\[ P = \sum_{i=1}^{n} S_i^4 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

\[ \mathbf{w}_{ij} = \sum_{i=1}^{n} \mathbf{w}_{ij} \mathbf{w}_{ij}^T \]

\[ \mathbf{b}_{ij} = \mathbf{b}_{ij} \]

Information Capacity

Space information

\[ \mathbf{a}_{ij,m}(f) = \mathbf{a}_{ij,m}^T(f)b_{ij,m}(f) + h_{ij,m}(f) \]

L2 norm and radiated power constraint:

\[ C = \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \]

where \( i, j, m \) are two non-negative constants chosen to satisfy the inequalities:

\[ \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \leq P \]

where \( \mathbf{P} \) is the radiated power constraint.

Accomplishments up Through Current Year

Since January 2005 we have been working on several fundamental problems in remote sensing that have resulted in publications in peer review journals.

2. In [7] we proposed a new non-iterative analytical alternative to the iterative numerical solution of the target scattering strength estimation proposed in [8].
3. In [11] we describe an alternative signal-subspace method which is based on searching for high-dimensional parameter space and which is found to adapt the time-reversal formulation to the number of realizable targets and in estimation variance.
4. This theory has been generalized to extended target and is currently under review for publication at the IEEE Transactions on Image Processing.

Opportunities for Technology Transfer

- Miller [2], [3] studied the orthogonal communication channels between two arbitrary volumes in free space radiating a scalar waves and, in a later generalization, [4] for volumes radiating electromagnetic waves.

- The scalar version of Miller’s work was later extended by Hanlen and Fu [5] to include the effect of scatterers in the propagation path.

- Gustafsson and Nordebo [6] analyzed the fundamental limitations in the capacity of an arbitrary electromagnetic antenna under Rayleigh fading channel and white Gaussian noise, obtaining into account antenna theory and broadband matching.

- Poon et al. [7] derived expressions for the NDF of a communication system with different array geometries and with a channel model based on measurements, providing upper bounds and lower bounds.

Challenges and Significance

In this work, we present the initial steps in using Shannon’s information theory to characterize the fundamental limits in the information transfer of a given device size under various physical constraints.

- In addition to the obvious applications in communication systems, the information theoretical concept used in this work is important in other applications like remote sensing where, for instance, we can characterize the performance of imaging systems in terms of the amount of information about the object contained in the image rather than how much the image resembles the object. Important challenges include the consideration of systematic as well as appropriate constraints.

Technical Approach

- Singular Value Decomposition (SVD)

\[ \mathbf{A} \mathbf{X} = \mathbf{Y} \]

Define:

\[ P = \sum_{i=1}^{n} S_i^2 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

SVD:

\[ P = \sum_{i=1}^{n} S_i^4 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

\[ \mathbf{w}_{ij} = \sum_{i=1}^{n} \mathbf{w}_{ij} \mathbf{w}_{ij}^T \]

\[ \mathbf{b}_{ij} = \mathbf{b}_{ij} \]

Information Capacity

Space information

\[ \mathbf{a}_{ij,m}(f) = \mathbf{a}_{ij,m}^T(f)b_{ij,m}(f) + h_{ij,m}(f) \]

L2 norm and radiated power constraint:

\[ C = \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \]

where \( i, j, m \) are two non-negative constants chosen to satisfy the inequalities:

\[ \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \leq P \]

where \( \mathbf{P} \) is the radiated power constraint.

Accomplishments up Through Current Year

Since January 2005 we have been working on several fundamental problems in remote sensing that have resulted in publications in peer review journals.

2. In [7] we proposed a new non-iterative analytical alternative to the iterative numerical solution of the target scattering strength estimation proposed in [8].
3. In [11] we describe an alternative signal-subspace method which is based on searching for high-dimensional parameter space and which is found to adapt the time-reversal formulation to the number of realizable targets and in estimation variance.
4. This theory has been generalized to extended target and is currently under review for publication at the IEEE Transactions on Image Processing.

Opportunities for Technology Transfer

- Miller [2], [3] studied the orthogonal communication channels between two arbitrary volumes in free space radiating a scalar waves and, in a later generalization, [4] for volumes radiating electromagnetic waves.

- The scalar version of Miller’s work was later extended by Hanlen and Fu [5] to include the effect of scatterers in the propagation path.

- Gustafsson and Nordebo [6] analyzed the fundamental limitations in the capacity of an arbitrary electromagnetic antenna under Rayleigh fading channel and white Gaussian noise, obtaining into account antenna theory and broadband matching.

- Poon et al. [7] derived expressions for the NDF of a communication system with different array geometries and with a channel model based on measurements, providing upper bounds and lower bounds.

Challenges and Significance

In this work, we present the initial steps in using Shannon’s information theory to characterize the fundamental limits in the information transfer of a given device size under various physical constraints.

- In addition to the obvious applications in communication systems, the information theoretical concept used in this work is important in other applications like remote sensing where, for instance, we can characterize the performance of imaging systems in terms of the amount of information about the object contained in the image rather than how much the image resembles the object. Important challenges include the consideration of systematic as well as appropriate constraints.

Technical Approach

- Singular Value Decomposition (SVD)

\[ \mathbf{A} \mathbf{X} = \mathbf{Y} \]

Define:

\[ P = \sum_{i=1}^{n} S_i^2 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

SVD:

\[ P = \sum_{i=1}^{n} S_i^4 \]

\[ \mathbf{J} \mathbf{X} = \mathbf{Y} \]

\[ \mathbf{w}_{ij} = \sum_{i=1}^{n} \mathbf{w}_{ij} \mathbf{w}_{ij}^T \]

\[ \mathbf{b}_{ij} = \mathbf{b}_{ij} \]

Information Capacity

Space information

\[ \mathbf{a}_{ij,m}(f) = \mathbf{a}_{ij,m}^T(f)b_{ij,m}(f) + h_{ij,m}(f) \]

L2 norm and radiated power constraint:

\[ C = \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \]

where \( i, j, m \) are two non-negative constants chosen to satisfy the inequalities:

\[ \sum_{i,j,m} \left( \int_{-f_0}^{f_0} \left| \mathbf{a}_{ij,m}(f) \right|^2 df \right) + \mathbf{b}_{ij,m}^T(f) \mathbf{b}_{ij,m}(f) \leq P \]

where \( \mathbf{P} \) is the radiated power constraint.