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DEFINING THE FUTURE

MIMO Radar Signal Processing of Space Time Coded Waveforms

IEEE Signal Processing Society
Baltimore Chapter Meeting
May 21, 2008

Dr. Marshall Greenspan
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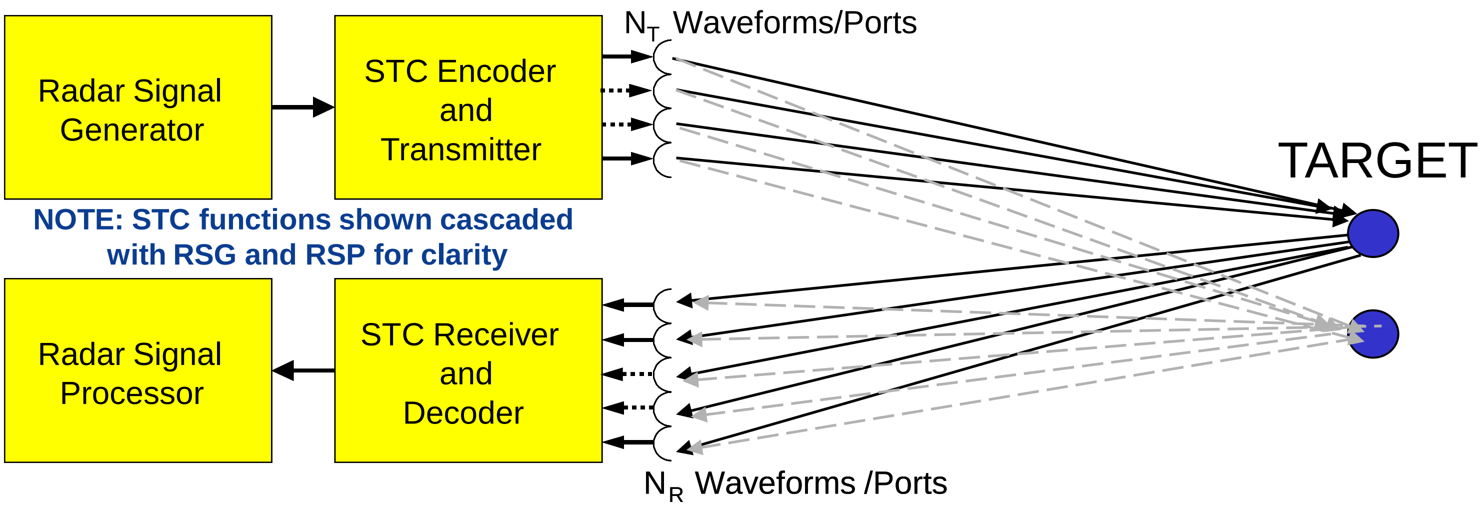
Northrop Grumman Corporation

Agenda

1. **What are MIMO Radar Systems?**
2. **What are Space-Time Coded Radar Waveforms?**
3. **What Can Space-Time Coded Radar Waveforms Accomplish with MIMO Radar System Architectures?**
4. **Questions and Answers**

Generic MIMO Radar Architecture



Note: Does not require uniformly spaced 1-D array of identical subarrays and all subarrays do not have to be both transmit and receive sites

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MIMO Radar Systems

- **MIMO stands for <u>M</u>ultiple <u>I</u>nput / <u>M</u>ultiple <u>O</u>utput**
  - **Closely related to (and often used interchangeably with) :**
    - Space-Time Coded (STC) Waveforms
    - Waveform Diversity (WFD)
- **Commonly Used in Communications Systems to Enhance Channel Capacity, Reduce Bit Error Rates & Signal Fading, and Extend Coverage Area**
  - **Now Being Proposed for Many Advanced Radar Applications**
- **Combines Spatially and Spectrally Diverse Waveforms from a Distributed Exciter with Multi-Port Receiver Channels to Create Additional Independent Propagation Paths**
  - **Officially a system that uses a multiplicity of spatially and spectrally separable waveforms and a multiplicity of spatially separable receivers**
  - **Sometimes also used to describe systems using only a single receiver but transmitting spectrally separable waveforms (i.e., WFD) or both spatially and spectrally separable (i.e., STC) waveforms**

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International Interest in MIMO Radar Systems

- **National & International Waveform Diversity Meetings**

1st Workshop	Feb. 4-7, 2003	Washington, DC
2nd Workshop	Feb. 2-4, 2004	Verona, NY
1st Conference	Nov. 8-10, 2004	Edinburgh, Scotland
3rd Workshop	Mar. 15-16, 2005	Huntsville, AL
2nd Conference	Jan. 22-27, 2006	Lihue, HI
4th Workshop	Nov. 14-15, 2006	Washington, DC
3rd Conference	Jun. 11-15, 2007	Pisa, Italy

- **Tutorials by Dan Bliss at MIT/LL ASAP Conferences in 2004 & 2005**
- **Large Number of Papers in Recent Technical Journals**
- **Special Waveform Diversity Sessions at 2008 IEEE Antenna and Propagation Society Symposium, 2008 MSS Tri-Service Radar Symposium, and other Radar-Related Conferences**

Key Benefits of MIMO Radar Architectures

- **Enhanced Target Detection**
  - Improved suppression of mainlobe and sidelobe clutter
  - Immunity to sidelobe discretes
  - Reduced sidelobes from sparse arrays
  - Higher SINR on slow-speed surface moving targets
  - Reduced target fading
  - Reduced need for transmit array calibration
- **Reduced Target Measurement Errors**
  - Improved angle accuracy at any target detection level
  - Enhanced Doppler resolution with same area coverage rate
  - Reduced susceptibility to multipath and propagation dispersion
- **Improved Area Coverage Rate**
  - Radar energy tailored to area of Interest
- **Reduced Vulnerability to Electronic Attack**
  - Denial of the radar waveform to a threat intercept receiver
  - Immunity to sidelobe repeaters
  - Reduced susceptibility to mainlobe deception

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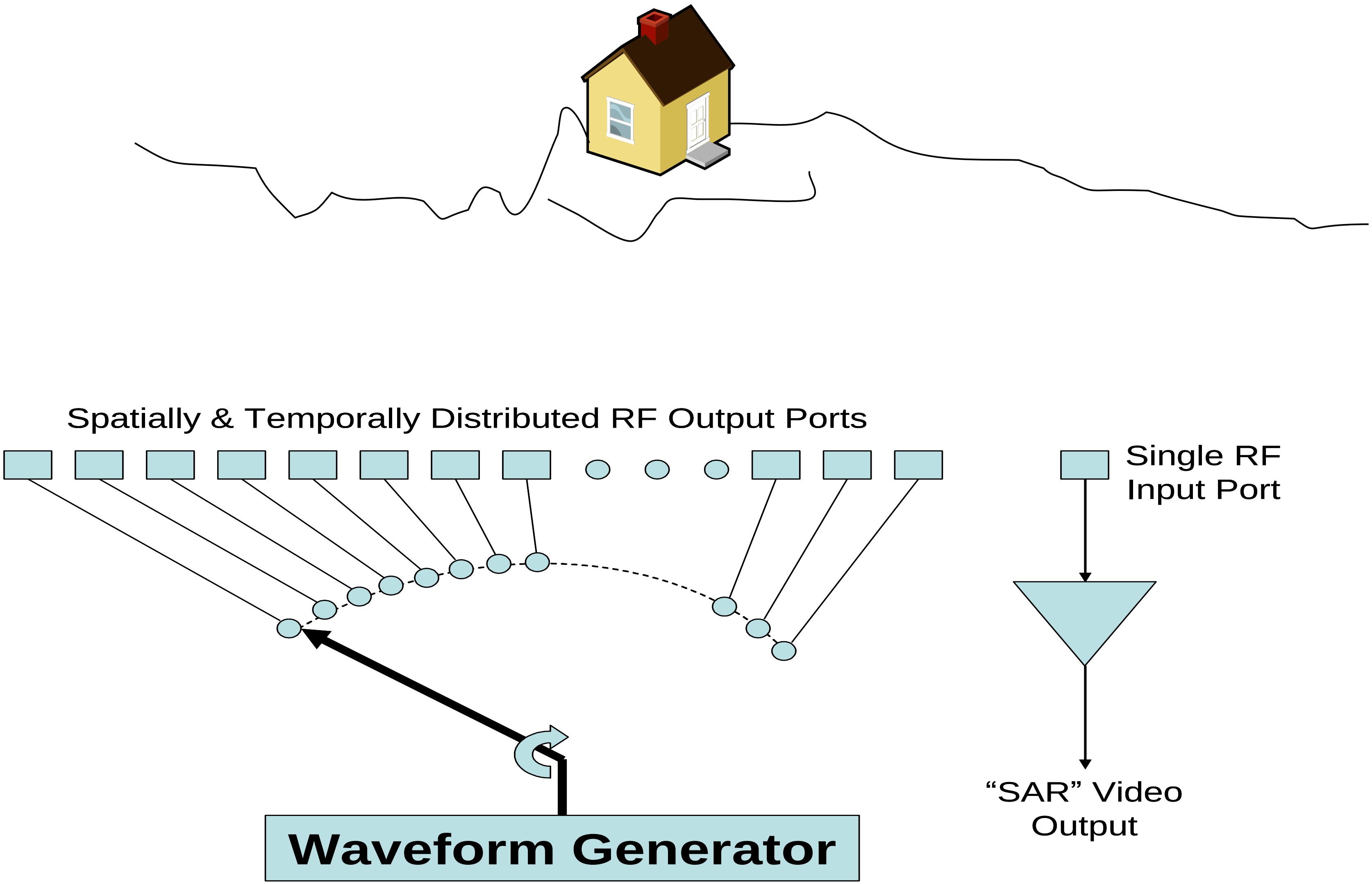
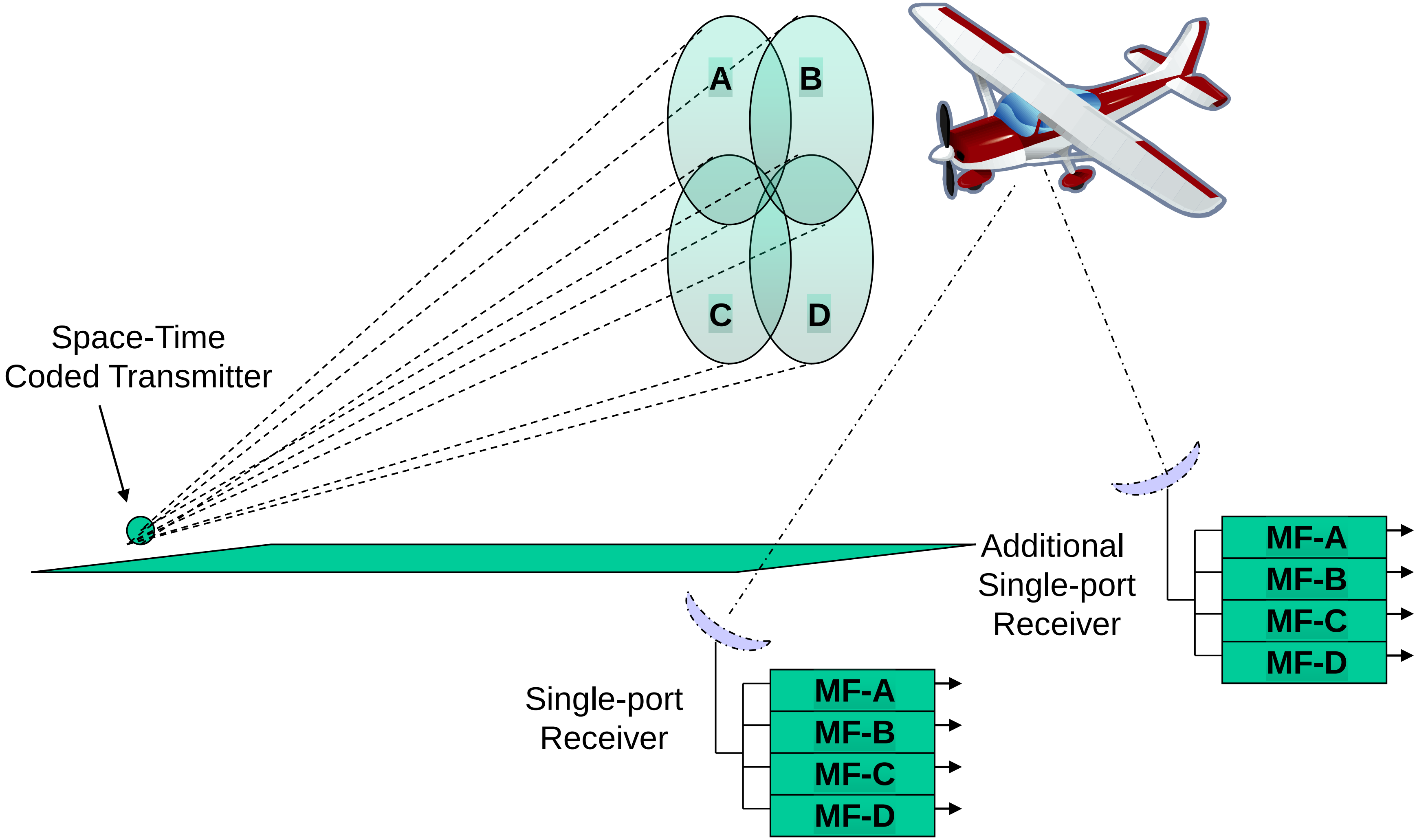
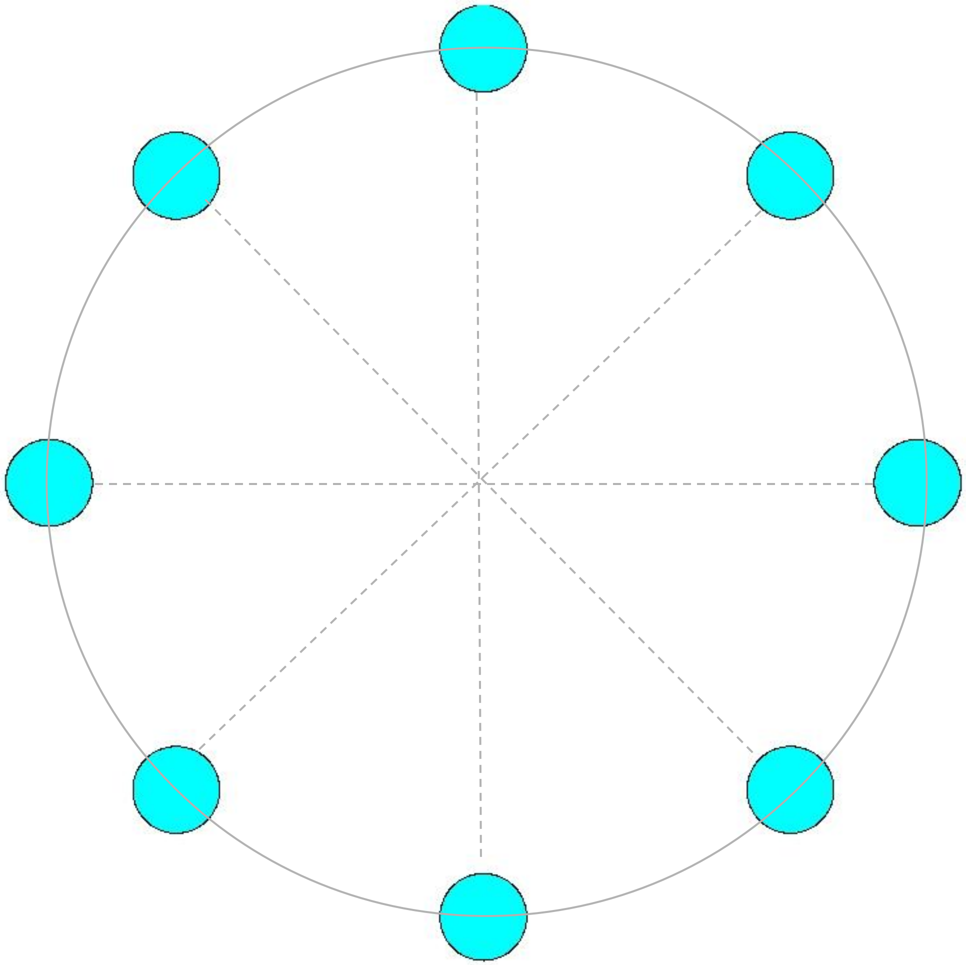
System Application: Mountain Top SAR

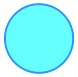


System Application: RF Glide Slope Indicator

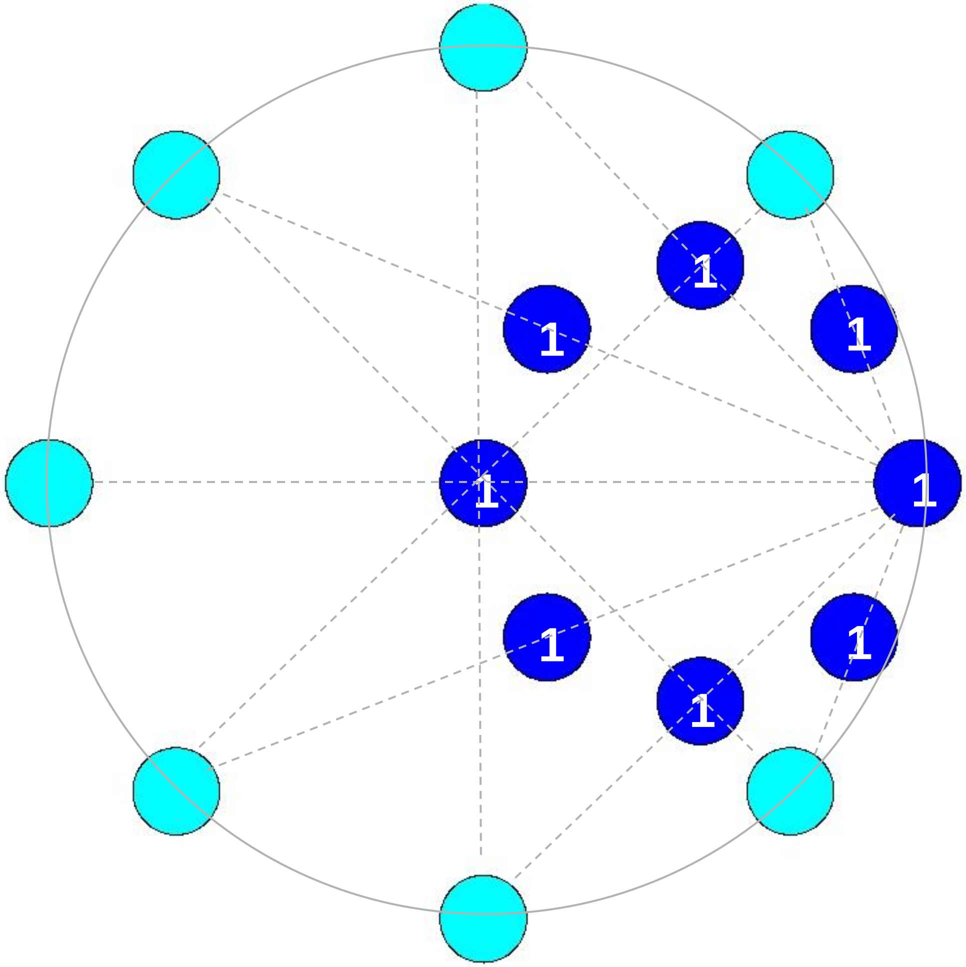


System Application: Filling of Sparse Arrays

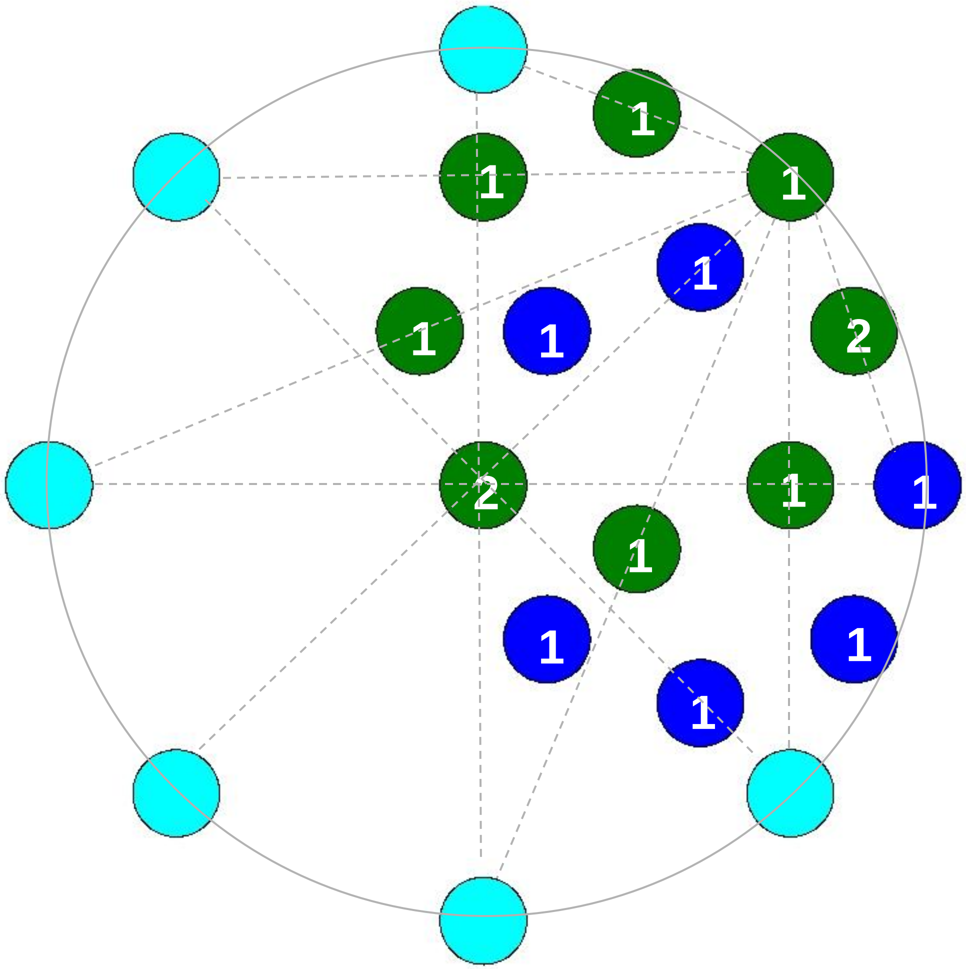


 = Physical Ports:

System Application: Filling of Sparse Arrays



System Application: Filling of Sparse Arrays



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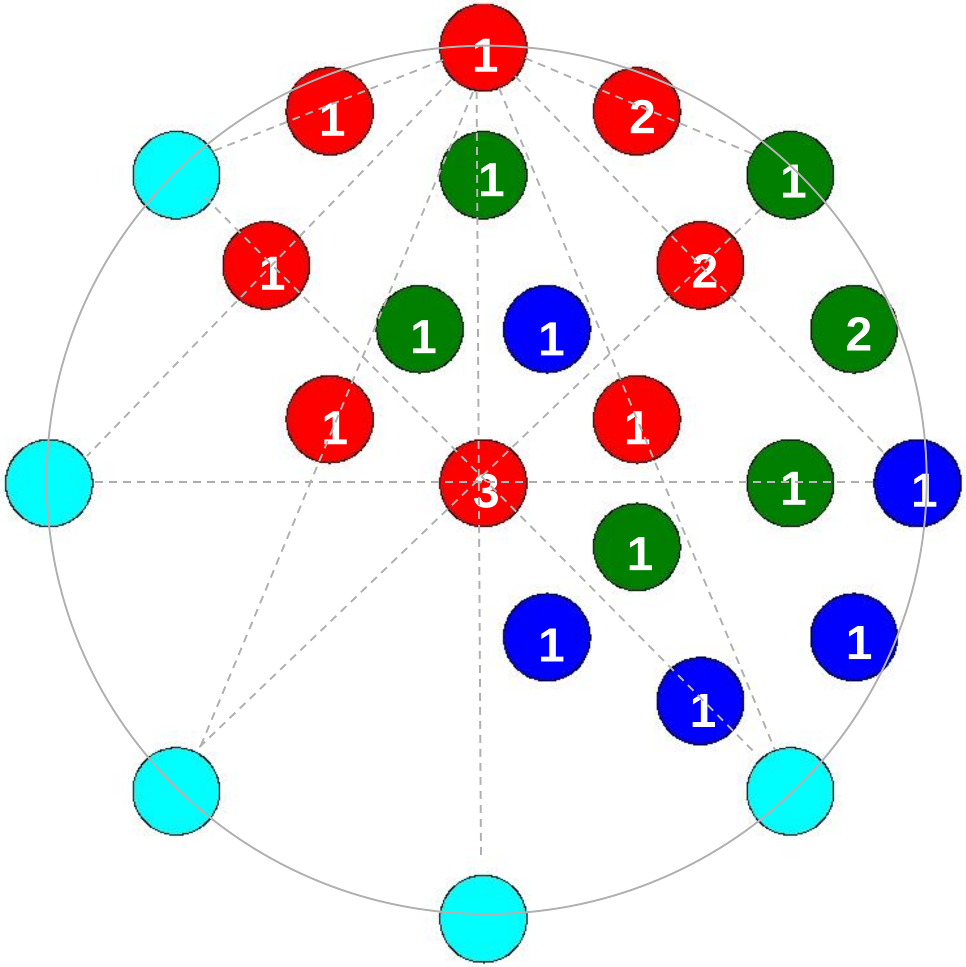
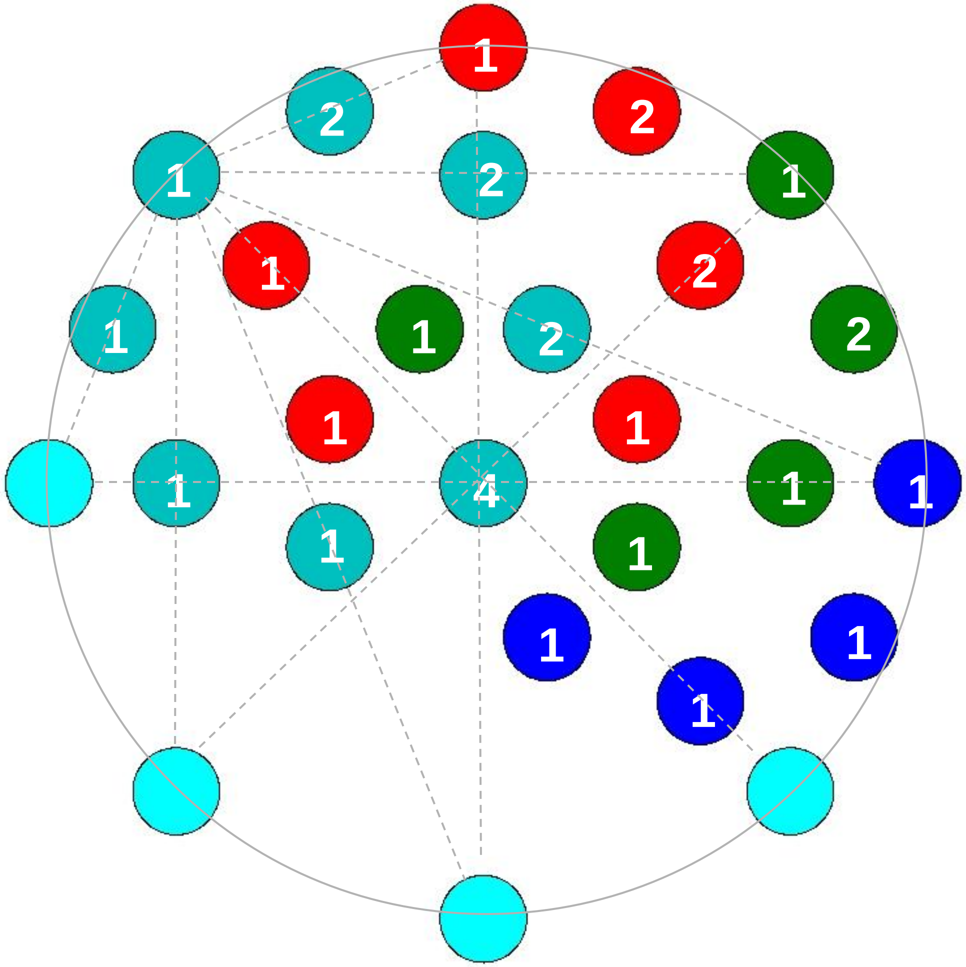
System Application: Filling of Sparse Arrays



System Application: Filling of Sparse Arrays



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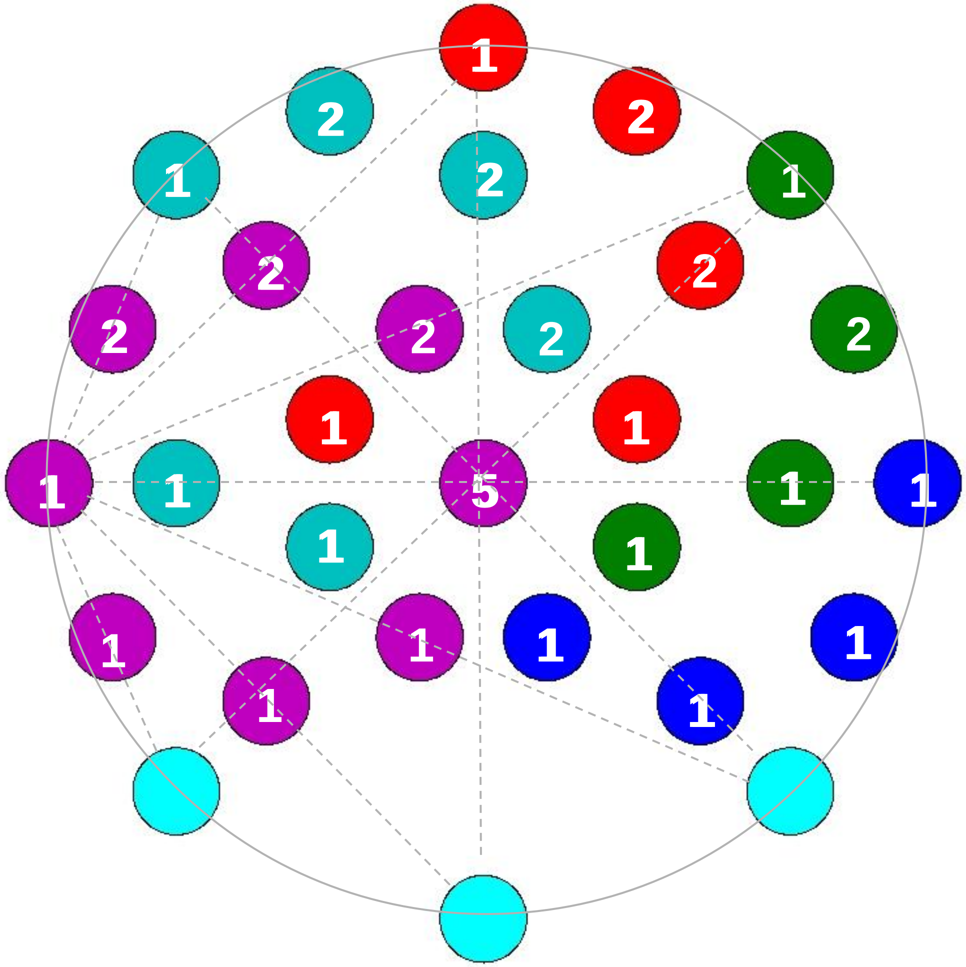
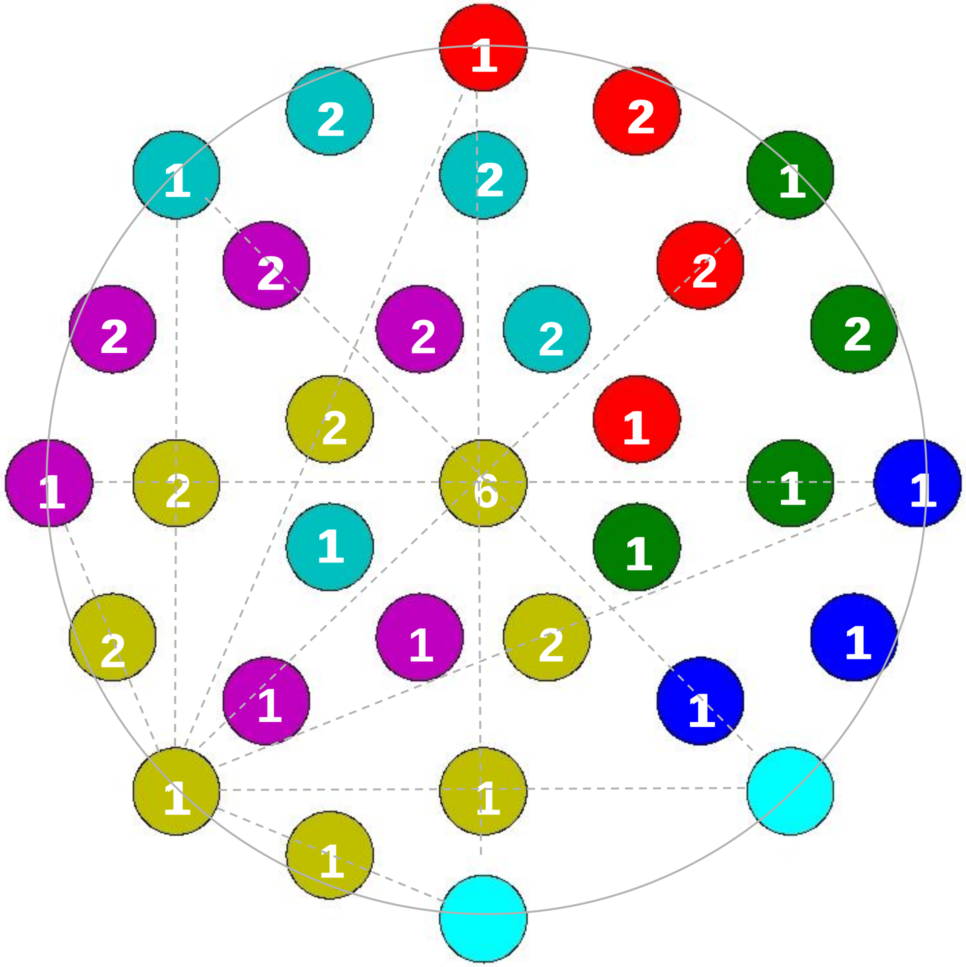
System Application: Filling of Sparse Arrays



System Application: Filling of Sparse Arrays



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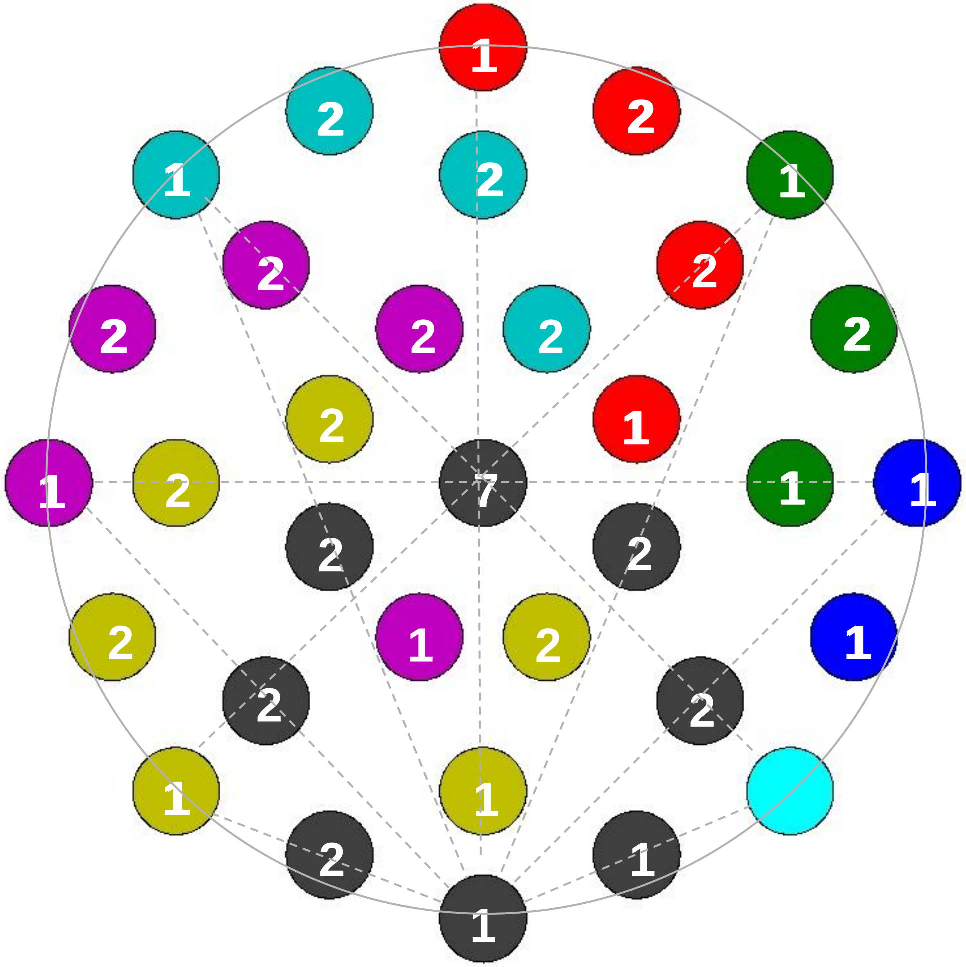
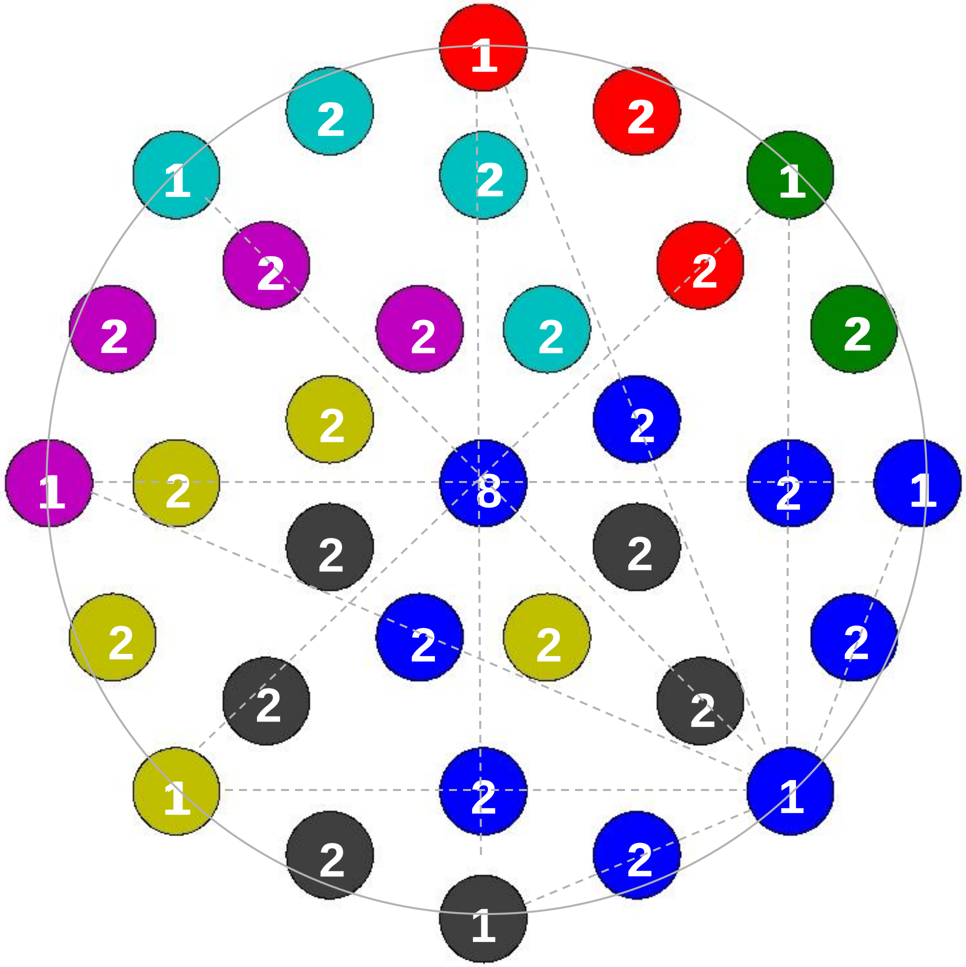
System Application: Filling of Sparse Arrays

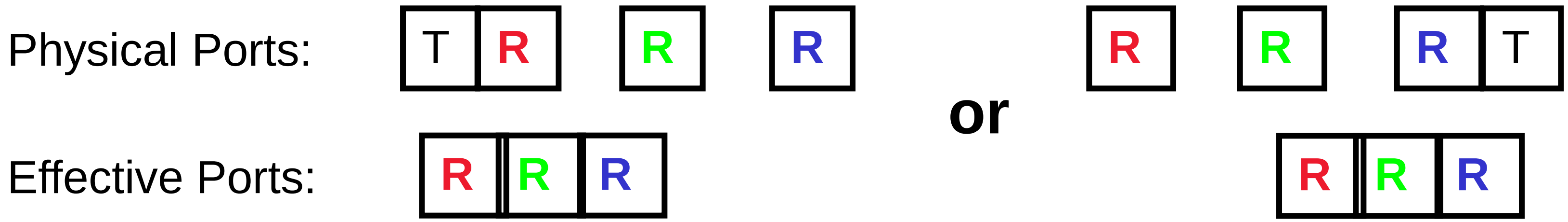


System Application: Filling of Sparse Arrays

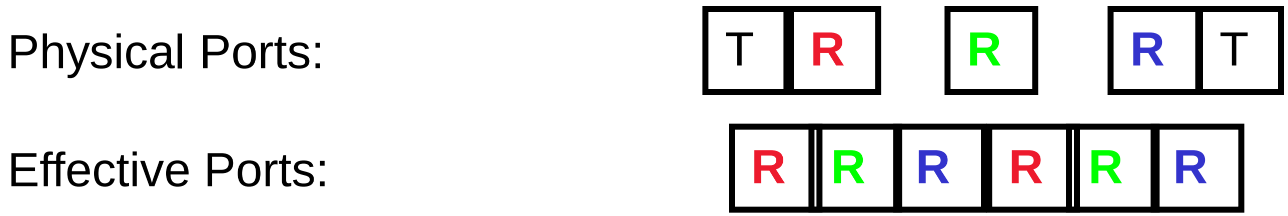


MIMO Angle Accuracy Enhancement

- **Effective Array with Single Port Transmitter**



- **Effective Array with Dual Space-Time Waveform Ports**

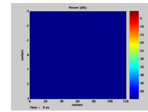


By Splitting Transmit Power Into Two Temporally or Spectrally Separable Waveforms Radiated from Spatially Separated Ports, Effective Array Length is Doubled and Angle Errors are Halved!

Space-Time Coded Waveform Domains

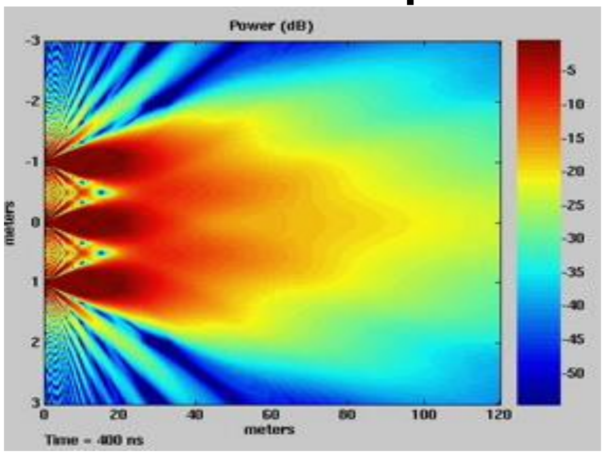
- **Time or Frequency Domain Distributions**
  - Time Division
    - Pulse-to-Pulse or Intra-Pulse Separations
  - Frequency Division
    - RF or Doppler Separations
  - Spectral Code Division
    - Simultaneously Present in the Same Region of both Time and Frequency
- **Spatial Domain Distributions**
  - Subarray Division
    - Signals Separated in Unique Subaperture Locations
  - Beam Division
    - Signals Separated in Unique Beam Directions
  - Spatial Code Division
    - Signals Dispersed in Multi-Dimensional Space

Classical Radar Waveforms

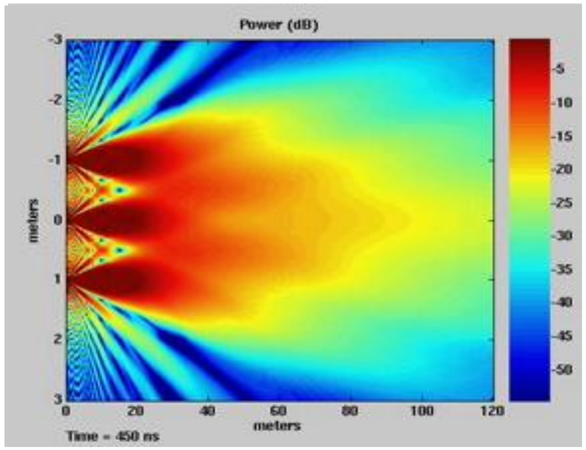


- **Usually Defined by Temporal or Spectral Properties**
  - pulse position, width, phase &/or amplitude modulation, carrier frequency, bandwidth, etc.
- **Also Inherently Characterized by Separate Spatial Properties**
  - aperture location, aperture amplitude and phase distribution, beam pointing, beam width, etc.

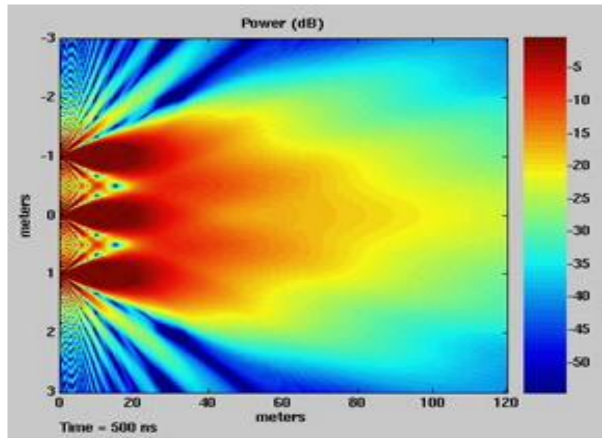
An Example: Three Identical Bi-Phase Code Sequences



T = 400 ns



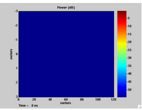
T = 450 ns



T = 500 ns

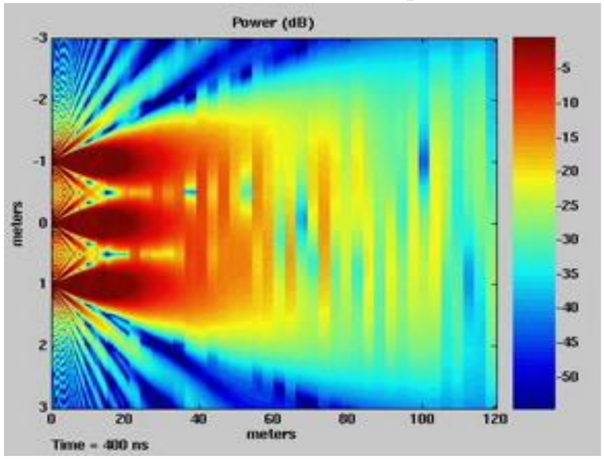
Since the 3 waveforms are fully correlated, the resultant spatial beam pattern is independent of time and the temporal waveform is independent of angle

Space-Time Coded Radar Waveforms

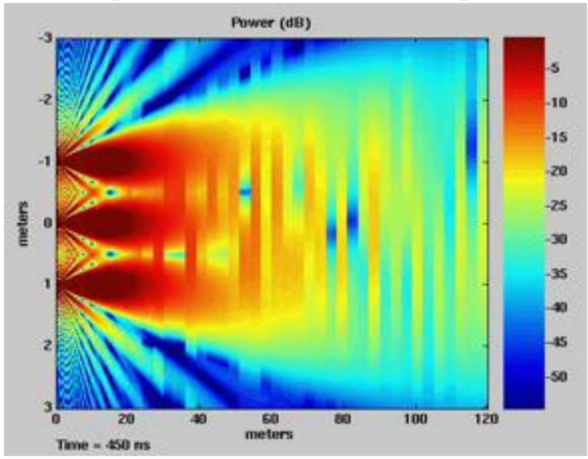


- **Blurs the Lines between Space and Time codes**
  - Time codes are a function of space
  - Spatial codes are a function of time
- **Tags Each Space Angle with a Unique & Separable Waveform**

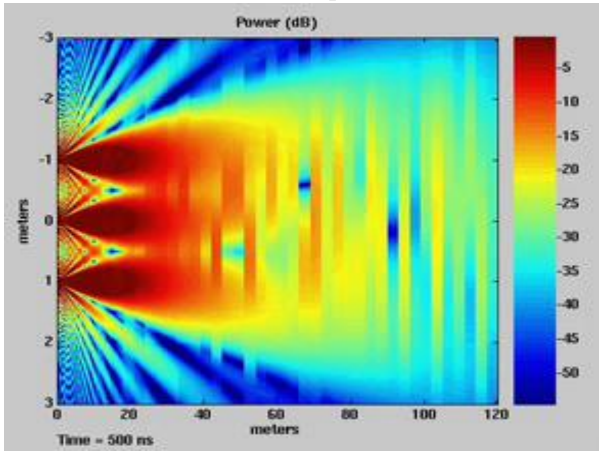
An Example: Three Separate 10ns/chip Bi-Phase Code Sequences



T = 400 ns



T = 450 ns



T = 500 ns

With uncorrelated waveforms at the array elements, the relative phases between the elements vary with time. This results in a time variable beam pattern or, equivalently, a composite waveform that varies with angle

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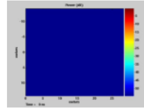
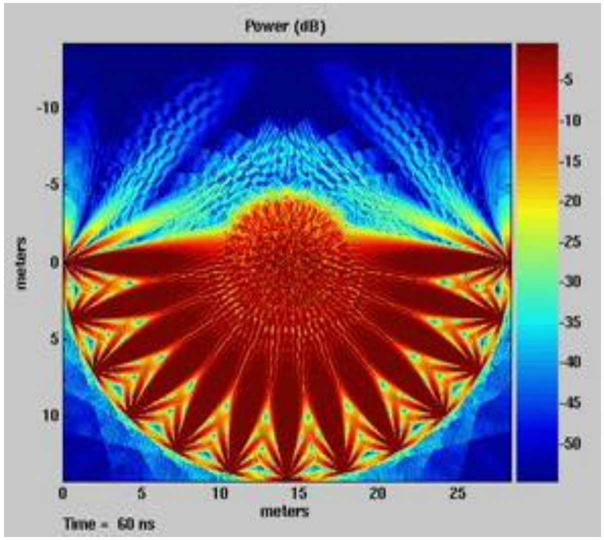
Circular Space-Time Coded Waveforms

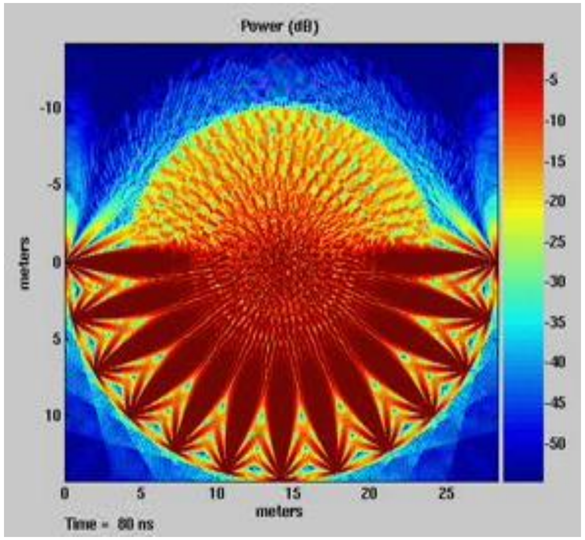


- **Nothing in Theory Restricts Aperture Distributions to be Planar**
- **Non-Planar Space-Time Coded Waveforms Capable of Tagging Each Point in Space with a Unique & Separable Waveform**

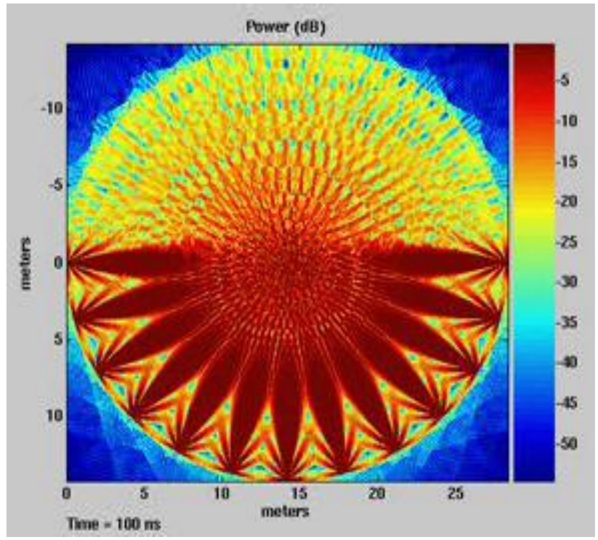
An Example: Thirteen Separate Non-Planar Bi-Phase Code Sequences



T = 60 ns



T = 80 ns



T = 100 ns

Unique and uncorrelated RF waveforms radiated from spatially-separated locations again result in RF fields that vary with both space and time

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Candidate Space-Time Coded Waveforms

- **The Key to MIMO Radar Systems:**
  - Spatial Diversity of Independent Waveforms
  - Provides “independent” views of target area
- **Three Generic Types of Independent Waveforms:**
  - Time (transmit at different times) Division Multiplexed
    - Simplest to Implement
    - Wasteful of dwell time and/or Doppler spectrum.
  - Frequency (transmit at different RF carriers) Division Multiplexed
    - Wasteful of available RF spectrum
  - Code (transmit with different phase codes) Division Multiplexed
    - Near optimal utilization of space, time, and spectrum allocations
    - Potentially high processing load

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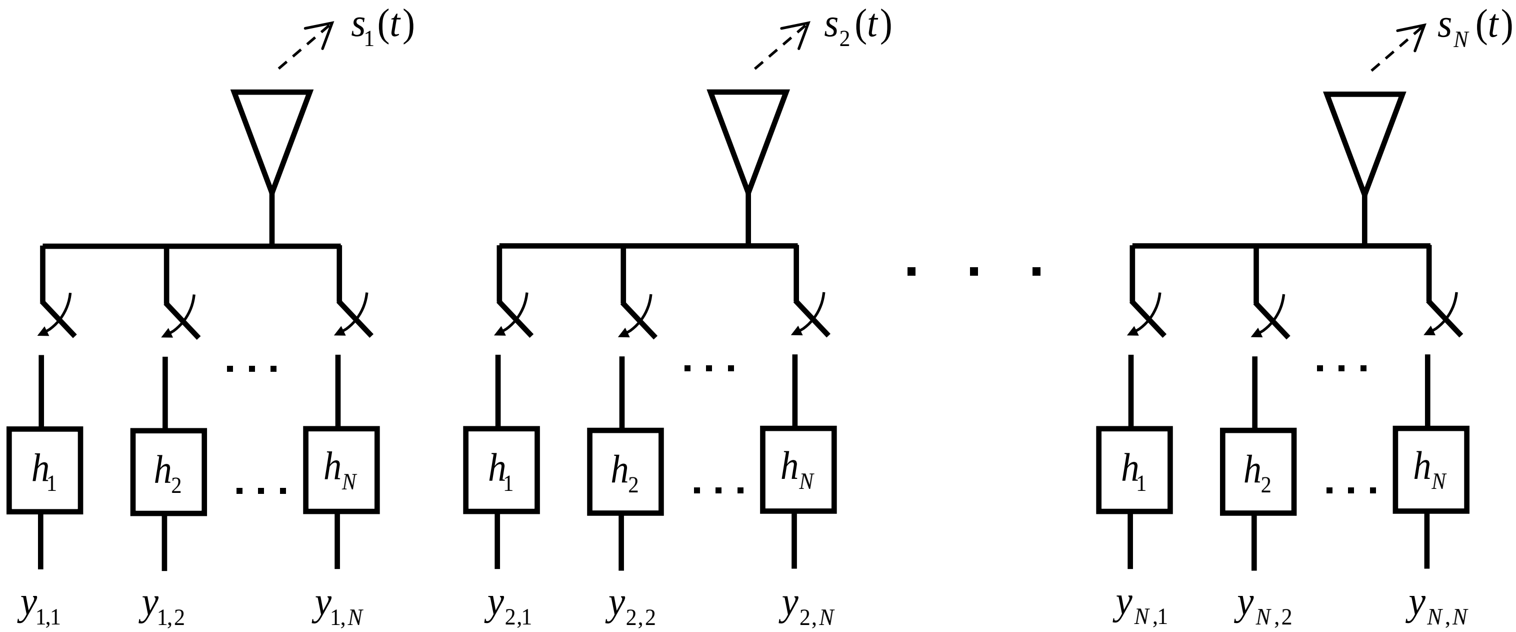
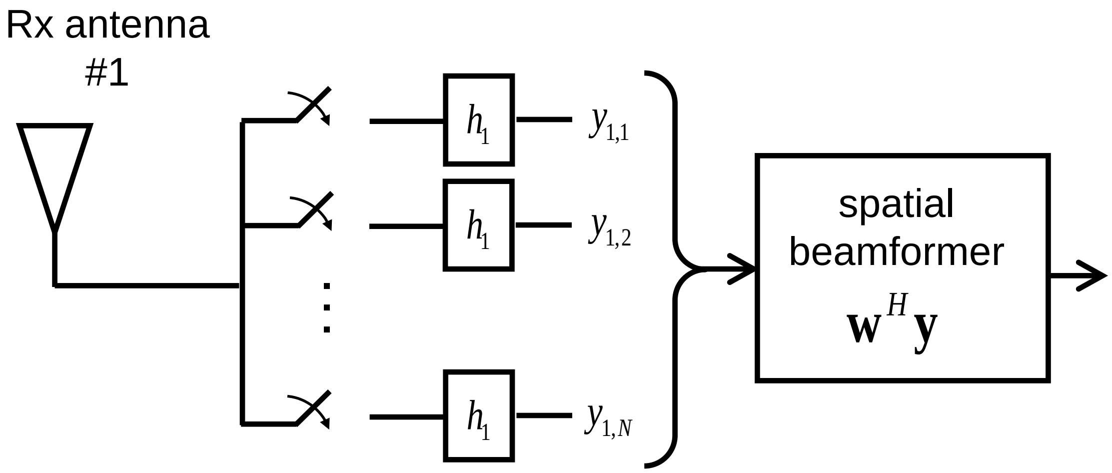
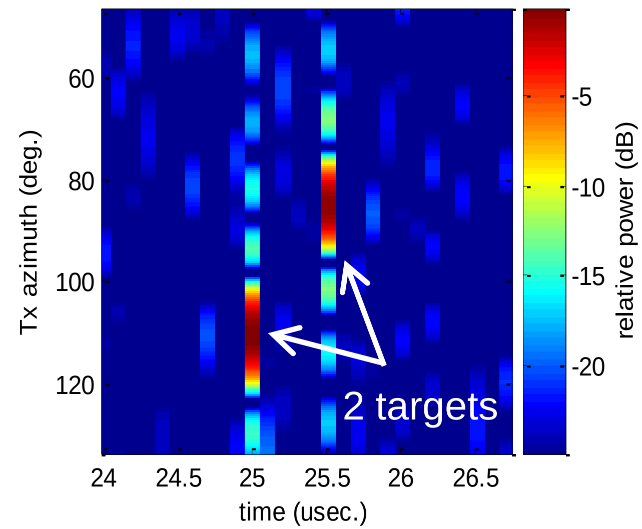
MIMO Processing Architecture



- **Filter h_n is matched to transmit signal $s_n(t)$ and has low correlation with all other signals**
- **Nominally requires a factor of up to N times more signal-matched filters than traditional single waveform systems**
- **<u>Note</u>: Peak transmit power density reduced by factor of up to N relative to use of common correlated waveforms**
- **<u>However</u>: Angular coverage extended by factor of up to N**
- **<u>And Furthermore</u>: SNR is recoverable via coherent addition of non-correlated waveforms within the digital signal processing domain**

“Transmit Beamform on Receive”





$$\mathbf{y} = [y_{1,1} \quad y_{1,2} \quad \cdots \quad y_{1,N}]^T$$

- **Requires waveforms with low cross correlation**
- **MIMO outputs from a single receive antenna can be beamformed to produce a desired transmit pattern**
- **Unique capabilities include:**
  - Different transmit patterns in each range bin
  - Angle estimation using a single receive antenna
  - Signal adaptive transmitter patterns

MIMO Papers by Dan Bliss (MIT/LL) & Others

- **Multiple-Input Multiple-Output (MIMO) Radar and Imaging: Degrees of Freedom and Resolution; Daniel Bliss, Keith Forsythe, MIT/LL, Session MA3b – Radar Array Processing; Asilomar 2003**
- **MIMO Radar: Resolution, Performance, and Waveforms. Daniel W. Bliss, Keith W. Forsythe, and Glenn S. Fawcett MIT/LL; ASAP 06 Conference**
- **Waveform Optimization for MIMO Radar: A Cramer-Rao Bound Based Study. Luzhou Xu, Jian Li, Peter Stoica, Keith W. Forsythe, and Daniel W. Bliss; SAM-L4: Space-Time Adaptive Processing and Waveform Design Session, ICASSP 2007.**
- **Low-Complexity Method for Transmit Beamforming in MIMO Radars; Tuomas Aittomäki, Visa Koivunen, Helsinki University of Technology, Finland; ITT-L1: Radar Signal Processing Session, ICASSP 2007**
- **F. Robey, "Enhancing Radar Array Performance through Space-Time Coding," Submitted to IEEE Trans. on Signal Processing. Contact fcr@ieee.org for pre-print.**

MIMO Radar: An Idea Whose Time Has Come

Eran Fishler - New Jersey Inst. of Tech., Alexander Haimovich - New Jersey Institute of Technology, Rick Blum - Lehigh University, Dmitry chizhik - Bell Labs - Lucent Technologies, Len Cimini - University of Delaware, Reinaldo Valenzuel - Bell Labs - Lucent Technologies; 2004 IEEE Radar Conference, Philadelphia, PA; Tue, 27 April 2004, 1:30 PM - 3:20 PM

Abstract: It has been recently shown that multiple-input multiple-output (MIMO) antenna systems have the potential to dramatically improve the performance of communication systems over single antenna systems. Unlike beamforming, which presumes a high correlation between signals either transmitted or received by an array, the MIMO concept exploits the independence between signals at the array elements. In conventional radar, target scintillations are regarded as a nuisance parameter that degrades radar performance. The novelty of MIMO radar is that it takes the opposite view, namely, it capitalizes on target scintillations to improve the radar's performance. In this paper, we introduce the MIMO concept for radar. The MIMO radar system under consideration consists of a transmit array with widely-spaced elements such that each views a different aspect of the target. The array at the receiver is a conventional array used for direction finding (DF). The system performance analysis is carried out in terms of the Cramer-Rao bound of the mean square error in estimating the target direction. It is shown that MIMO radar leads to significant performance improvement in DF accuracy.

MIMO Radar

This research will focus upon MIMO systems applied to Radar transmitters and receivers. One of the objectives is to find out whether using multiple Radar transmitters and receivers similar to the MIMO wireless communication principle makes any fundamental difference to the RADAR technology. Other potential research areas will be considered are tracking multiple sources using multiple digital-beams and 3-D location identification using geographically separated multiple receive antennas. Furthermore, this research work will also rekindle Radar information theory field which has been laying dormant since 1950's and may lead to breakthroughs in radar technology.

Funding: EPSRC and QinetiQ, Portsmouth

Members: Dr Mathini Sellathurai ; Dr T Ratnarajah; David Wilcox

Statistical MIMO Radar

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ECE Department
Lehigh University

Collaborative Research with:
Eran Fishler/NJIT
Alex Haimovich/NJIT
Dmitry Chizhik/Bell Labs
Len Cimini/U. Del.
Reinaldo Valenzuela/Bell Labs

Performance of MIMO Radar Systems: Advantages of Angular Diversity

- **Fishler, E.; Haimovich, A.; Blum, R.; Cimini, R.; Chizhik, D.; Valenzuela, R. Signals, Systems and Computers, 2004. Conference Record of the Thirty-Eighth Asilomar Conference on Volume 1, Issue , 7-10 Nov. 2004 Page(s): 305 - 309 Vol.1**
  Digital Object Identifier 10.1109/ACSSC.2004.1399142

- Summary: **Inspired by recent advances in multiple-input multiple-output (MIMO) communications, this paper introduces the statistical MIMO radar concept. The fundamental difference between statistical MIMO and other radar array systems is that the latter seek to maximize the coherent processing gain, while statistical MIMO radar capitalizes on the diversity of target scattering to improve radar performance. Coherent processing is made possible by highly correlated signals at the receiver array, whereas in statistical MIMO radar, the signals received by the array elements are uncorrelated. It is well known that in conventional radar, slow fluctuations of the target radar cross-section (RCS) result in target fades that degrade radar performance. By spacing the antenna elements at the transmitter and at the receiver such that the target angular spread is manifested, the MIMO radar can exploit the spatial diversity of target scatterers opening the way to a variety of new techniques that can improve radar performance. In this paper, we focus on the application of the target spatial diversity to improve detection performance. The optimal detector in the Neyman-Pearson sense is developed and analyzed for the statistical MIMO radar. An optimal detector invariant to the signal and noise levels is also developed and analyzed. In this case as well, statistical MIMO radar provides great improvements over other types of array radars**

Summary

- **Space-Time Coded Waveforms and MIMO Radar Architectures Will Play an Important Role in Future Radar Systems**
  - Compatible with On-Going Northrop Grumman Electronic Systems Developments of Advanced Hardware Components
    - Multi-Aperture Arrays
    - Distributed Exciters
    - Flexible Arbitrary Waveform Generators
    - Programmable Wideband Receiver Filters
- **Will Provide Additional Degrees of Freedom to the Radar System Designer to Achieve Performance Unavailable by Any Other Means**
- **Will Challenge the System Architect to Find Affordable Configurations that Take Fullest Advantage of the New Design Options**

Questions