Design and Evaluation of a Multi-Modulation Retrodirective RFID Tag

Mohammad Alhassoun
Michael Varner
Prof. Gregory Durgin

The Propagation Group
Georgia Institute of Technology

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Problem Overview

Next-generation IoT sensors should

- **Operate at high frequencies (mm-waves)**
- **Have high gain (reasonable communication distance)**
- **Be orientational independent**
- **Consume minimal power**

Possible Solutions

Problems

1. High gain tags
2. Orientation-independent tags

Solutions

1. Use antenna arrays
2. Use isotropic (or semi-isotropic) antennas

From antenna theory, you cannot do both!

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The *Best* Solution

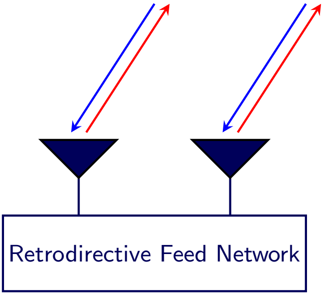
- We cannot use active beamformers because power consumption
- Alternatively, we can use retrodirective arrays

Retrodirective arrays are the best RF-based solution to compensate for

1. *Narrow beamwidth of passive arrays*
2. *Short range of high-frequency tags*

Retrodirective Arrays: Definition

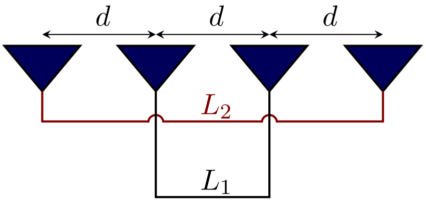
- Retrodirective arrays send waves back to the direction of incidence.
- Ideally, no power loss and maximum gain (in optics, similar to corner reflectors)



Retrodirective arrays act as passive, adaptive beamformers

Retrodirective Arrays: Example

- *Van Atta* arrays
- Connects each antenna pair by a transmission lines $L_2 = L_1 + n\lambda_m$

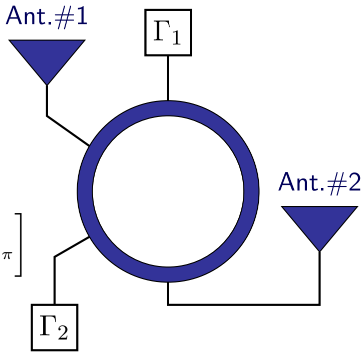


Problems with Van Atta array are:

1. Limited to OOK or at best BPSK
2. You cannot incorporate two-terminal devices (e.g., tunnel diodes)

Proposal

- A rat-race coupler can be a retrodirective feed network.
- The two port scattering matrix is



$$[S] = \frac{1}{2}\begin{bmatrix} (\Gamma_1+\Gamma_2)e^{-j\pi} & (\Gamma_1-\Gamma_2) \\ (\Gamma_1-\Gamma_2) & (\Gamma_1+\Gamma_2)e^{-j\pi} \end{bmatrix}$$

Conditions

1. $|\Gamma_1| = |\Gamma_2|$
2. $\angle\Gamma_2 = \angle\Gamma_1 + \pi$

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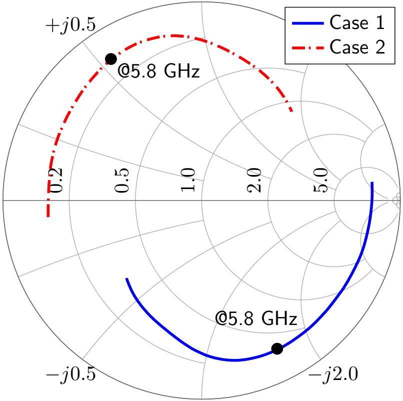
Examples of Terminations

1. Port 1 is open $\Rightarrow \Gamma_1 = 1$
   Port 2 is short $\Rightarrow \Gamma_2 = -1$

2. Port 1 is short $\Rightarrow \Gamma_1 = -1$
   Port 2 is open $\Rightarrow \Gamma_2 = 1$

Observation

In both cases, the coupler is retrodirective; however, two (opposite) locations on Smith Chart.



More to say

- **Switching between retrodirective terminations changes only the phase**
- **Switching between a retrodirective and non-retrodirective state implements OOK**
- **No restrictions on the type of terminations**

Now, it is time to test the RCS of the device

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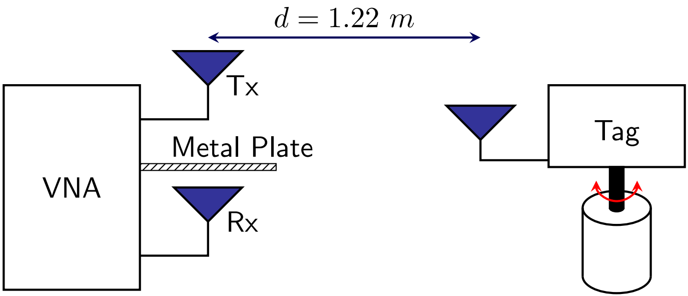
Set Up



Specifications

- **Location**: Rooftop of the building (open range)
- **Power**: 25 dBm (+6 dBi antenna gain)
- **Frequency Span**: $(3.8 - 7.8)$ GHz (4 GHz BW)
- **Angular Span**: -90° to 90°
- **Target Height**: $1.73\ cm$
- **Post-Processing Technique**: Time Gating
- **Tag designs**:
  1. Retrodirective (BPSK and OOK)
  2. Single-element (BPSK and OOK)

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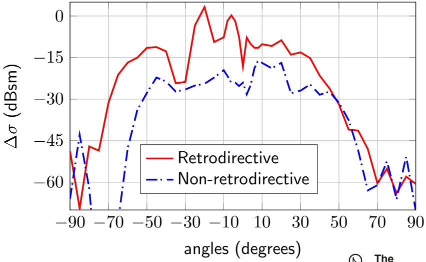
BPSK Configuration and Results

Recall

A rat-race coupler is retrodirective if $|\Gamma_1| = |\Gamma_2|$ and $\angle\Gamma_2 = \angle\Gamma_1 + \pi$

- For retrodirective tag:
  State#1: $\Gamma_1 = 1$, $\Gamma_2 = -1$
  State#2: $\Gamma_1 = -1$, $\Gamma_2 = 1$
- For single antenna tag:
  State#1: Open circuit
  State#2: Short circuit
- The measured differential RCS



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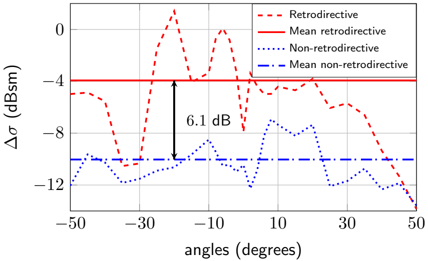
BPSK: Global Performance

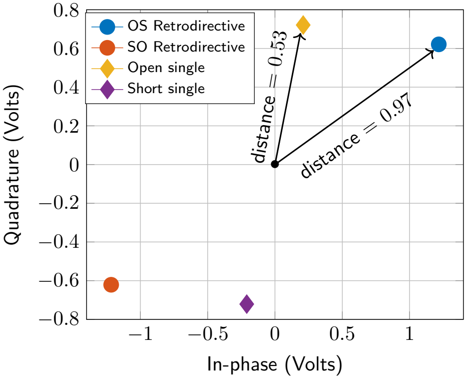
We expect 6 dB increase in the differential RCS

- What if we look at the global performance?
- Within the beamwidth of the (patch) antenna, how much increase on average?



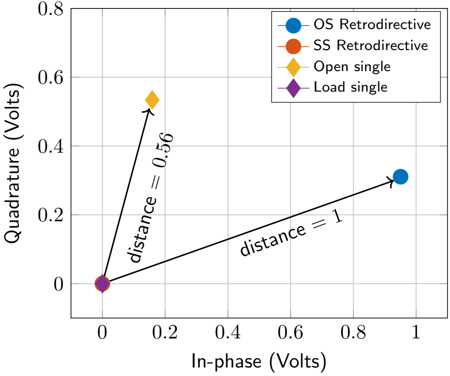
BPSK: Constellations

- For retrodirective tag:
  State#1: $\Gamma_1 = 1$, $\Gamma_2 = -1$
  State#2: $\Gamma_1 = -1$, $\Gamma_2 = 1$
- For single-antenna tag:
  State#1: Open circuit
  State#2: Short circuit



OOK: Constellations

- For retrodirective tag:
  State#1: $\Gamma_1 = 1$, $\Gamma_2 = -1$
  State#2: $\Gamma_1 = -1$, $\Gamma_2 = -1$
- For single-antenna tag:
  State#1: Open circuit
  State#2: $50\ \Omega$ Load



Retrodirectivity Ideality Facor (RIF): Why?

- We want to measure the performance of the a retrodirective feed network
- Phase is the *most* important quantity
- Phase of the feed network must be compared with an ideal retrodirective network
- The ideal feed network is that of Van Atta arrays, a simple TEM Transmission line

Therefore, we introduced a new metric: The Retrodirectivity Ideality Facor (RIF)

Retrodirectivity Ideality Facor (RIF): Definition

Definition

Maximum deviations between the samples of the measured phase and the samples of the *interpolated* equivalent linear phase.

$$\max\{RIF_j\}, \quad \forall j = 1, \ldots, \#\text{of states}$$

$$RIF = 1 + \frac{\sum_{i=1}^{N} (\Phi_{i,21} - \hat{\Phi}_{i,21})^2}{\sum_{i=1}^{N} \hat{\Phi}_{i,21}^2}$$

Retrodirectivity Ideality Facor (RIF): Measured

Definition

Maximum deviations between the samples of the measured phase and the samples of the *interpolated* equivalent linear phase.

- The definition is valid *only* within the bandwidth.
- For BPSK,

$$BW \in (5.7 - 5.85)\ \text{GHz}$$
$$\max\{1.0003, 1.0001\} = 1.0003$$

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Retrodirectivity Loss Factor (RLF): Motive

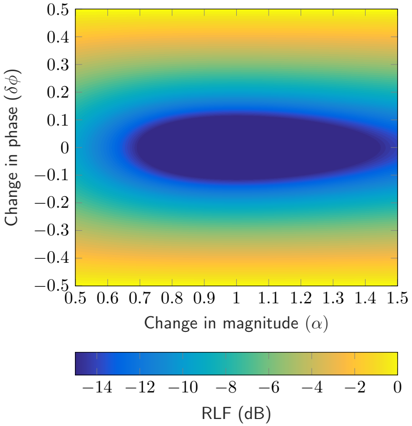
Recall

A rat-race coupler is retrodirective if $|\Gamma_1| = |\Gamma_2|$ and $\angle\Gamma_2 = \angle\Gamma_1 + \pi$

- Two constraints: Magnitude and Phase; but, to which the design is more sensitive?
- Mathematically,

$$RLF = \left| \frac{1 + \alpha e^{j\pi(1+\delta\phi)}}{1 - \alpha e^{j\pi(1+\delta\phi)}} \right|^2$$

Retrodirectivity Loss Factor (RLF): Result



$$RLF = \left| \frac{1 + \alpha e^{j\pi(1+\delta\phi)}}{1 - \alpha e^{j\pi(1+\delta\phi)}} \right|^2$$

Phase sensitive

Summary

In this paper, we

- Designed a retrodirective feed network using a rat-race coupler
- Derived the retrodirectivity conditions for the coupler
- Showed the proposed feed network is capable implemented various modulation schemes.
- Developed two metrics to evaluate retrodirectivity
  1. Retrodirectivity Ideality Factor (RIF) {Recast}
  2. Retrodirectivity Loss Factor (RLF)

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