Design and Evaluation of a Multi-Modulation Retrodirective RFID Tag

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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!
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 ⇒ \( \Gamma_1 = 1 \)
   Port 2 is short ⇒ \( \Gamma_2 = -1 \)

2. Port 1 is short ⇒ \( \Gamma_1 = -1 \)
   Port 2 is open ⇒ \( \Gamma_2 = 1 \)

**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
Set Up

$d = 1.22 \ m$

VNA

Tx

Metal Plate

Rx

Tag
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**: $-90^\circ$ to $90^\circ$
- **Target Height**: 1.73 cm
- **Post-Processing Technique**: Time Gating
- **Tag designs**:
  1. Retrodirective (BPSK and OOK)
  2. Single-element (BPSK and OOK)
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

![Diagram of RCS angles and differential RCS](image-url)
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?

![Graph showing Δσ (dBsm) vs angles (degrees)]
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

![Graph showing BPSK constellations](image-url)
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

![Graph showing OOK: Constellations with States and Voltages]
Retrodirectivity Ideality Factor (RIF): Why?

- We want to measure the performance of the 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 Factor (RIF)*
Retrodirectivity Ideality Factor (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,

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

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

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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)