RFocus: Beamforming using 1000s of Passive Antennas

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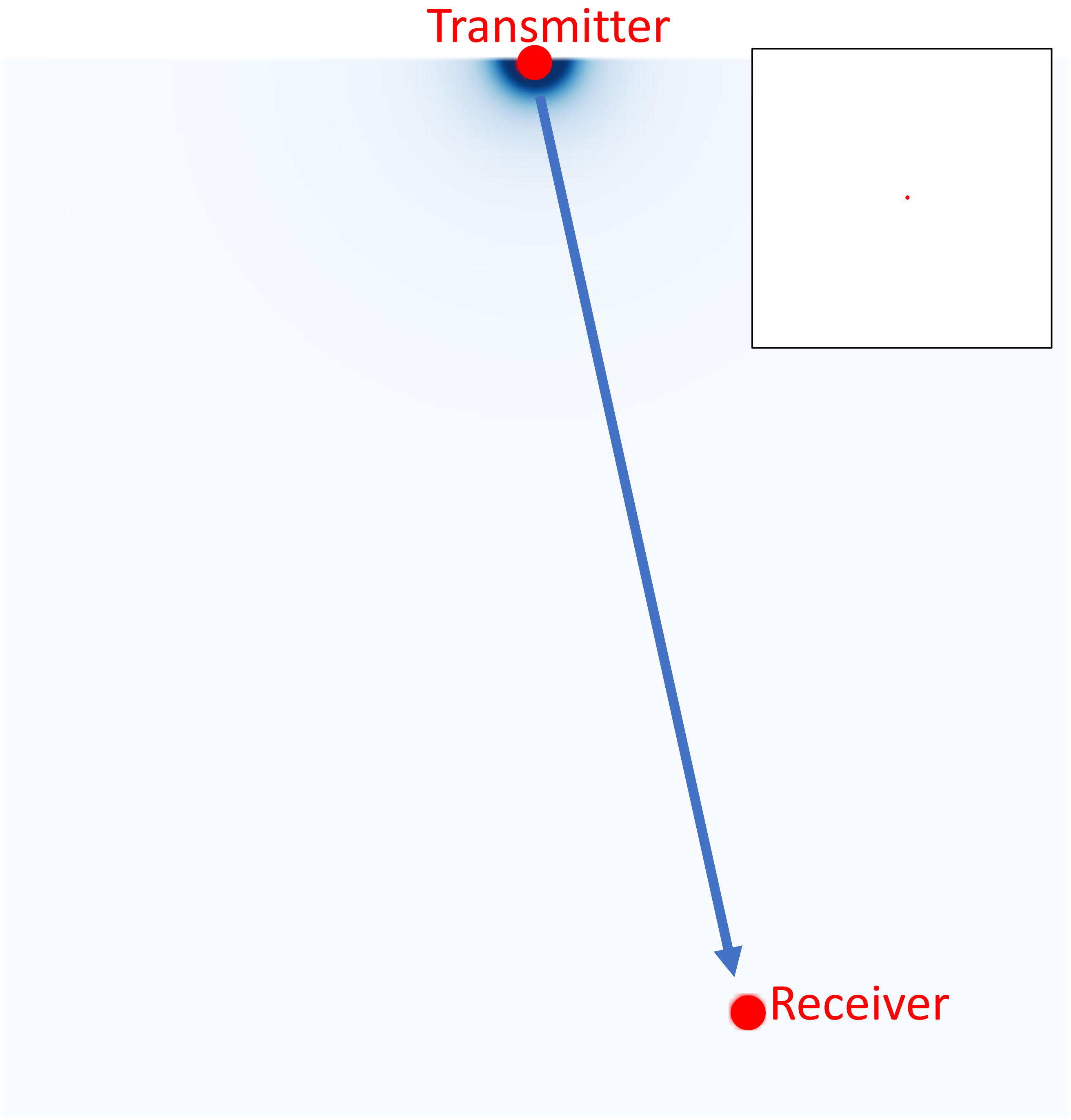
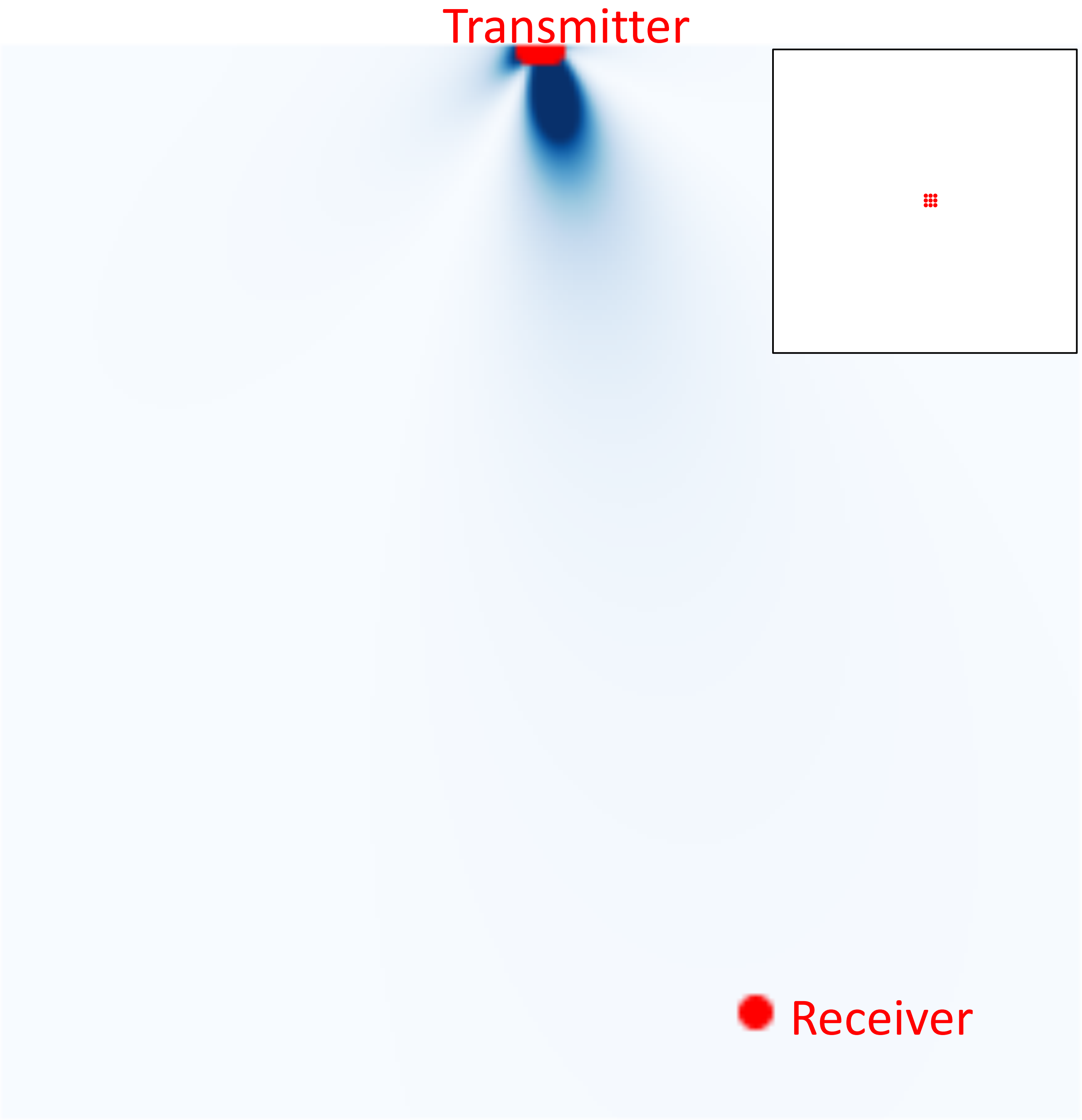
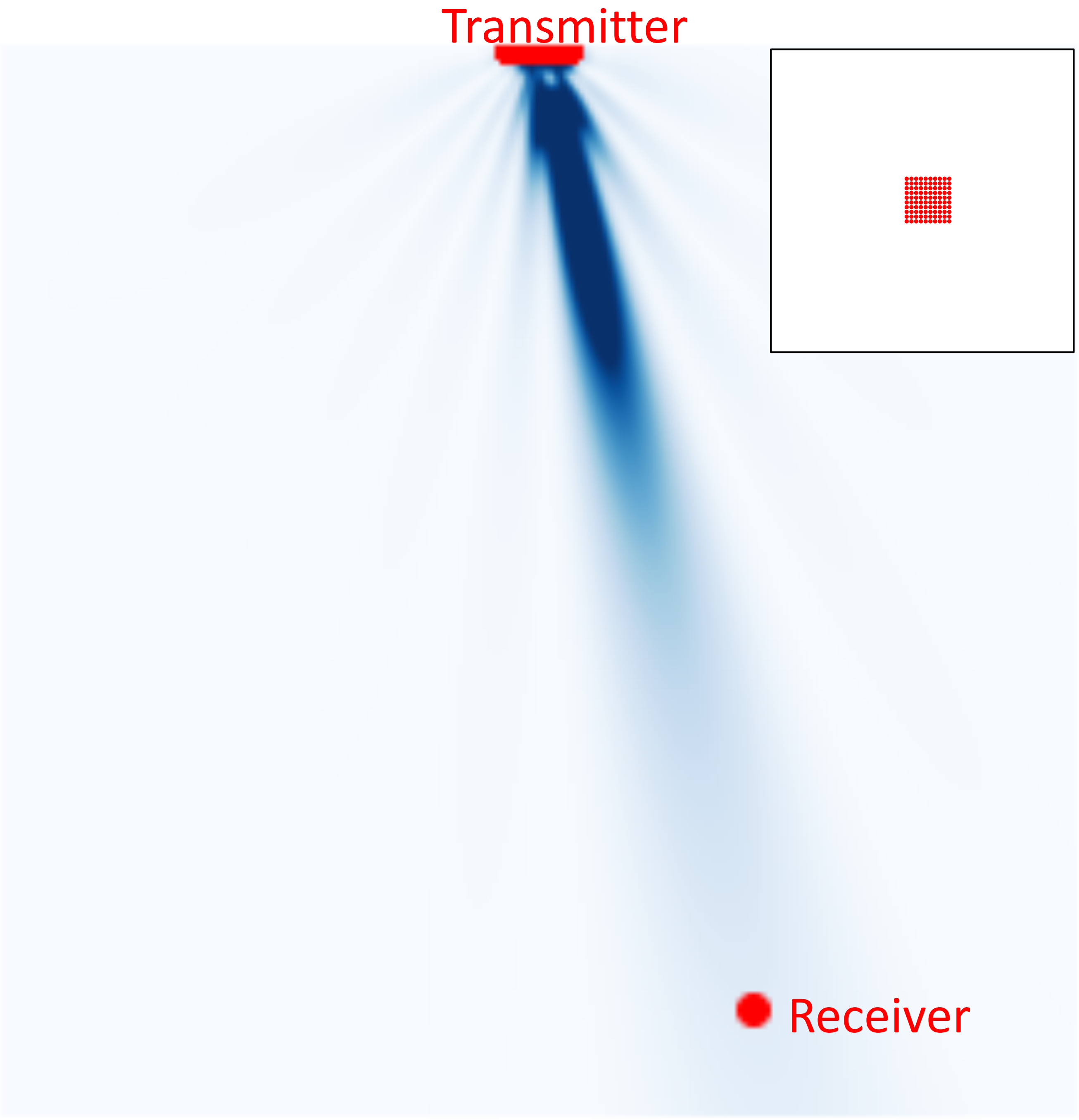


1 Antenna

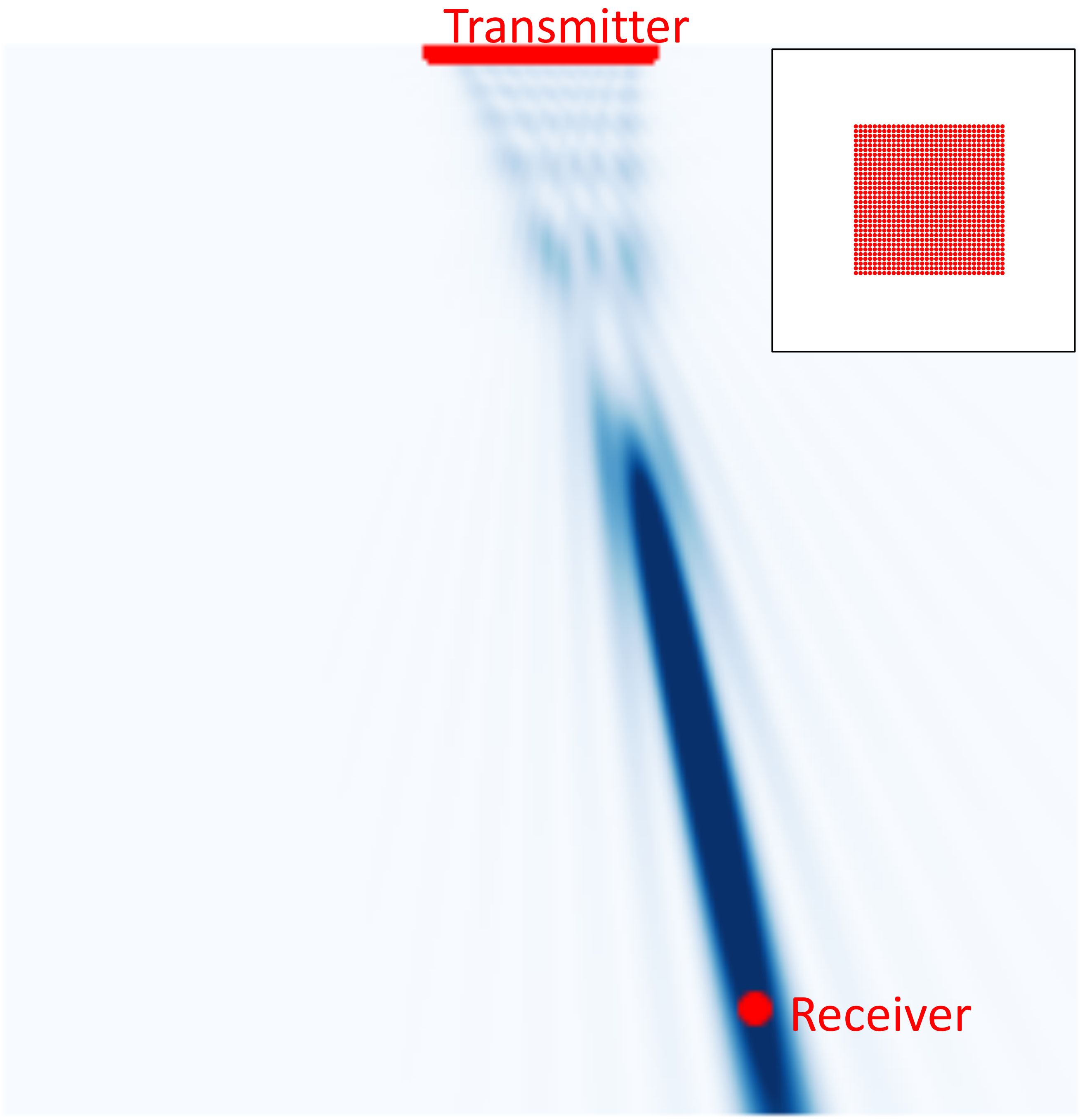
Goal: Maximize signal strength at receiver



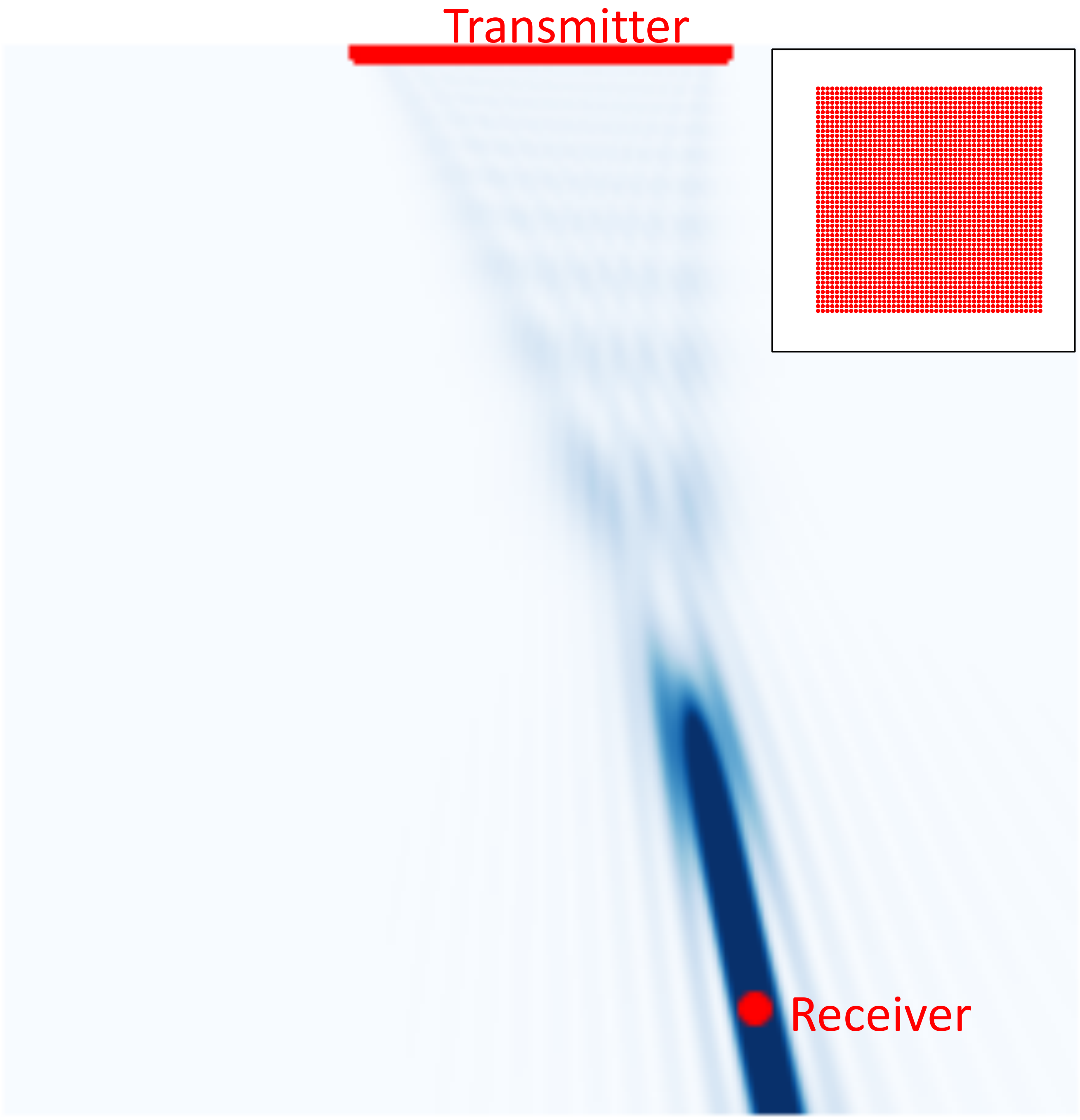
9 Antennas



100 Antennas

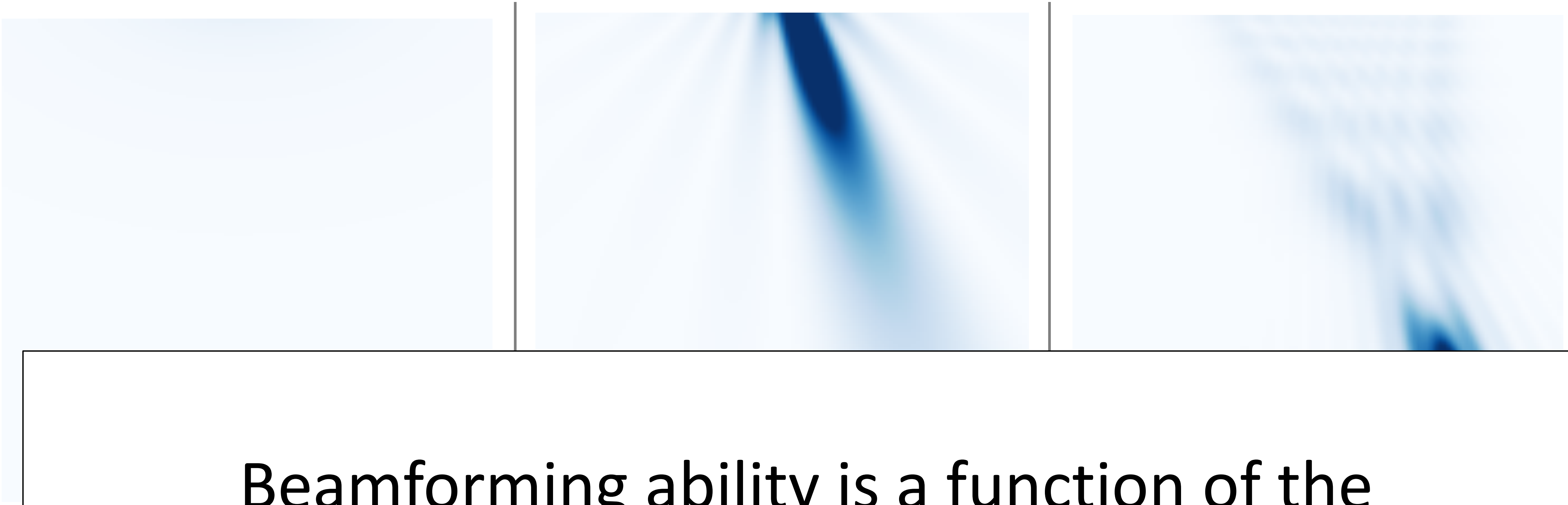


1024 Antennas



3136 Antennas

1 Antenna 100 Antennas 3136 Antennas



Beamforming ability is a function of the number of wavelengths the device spans

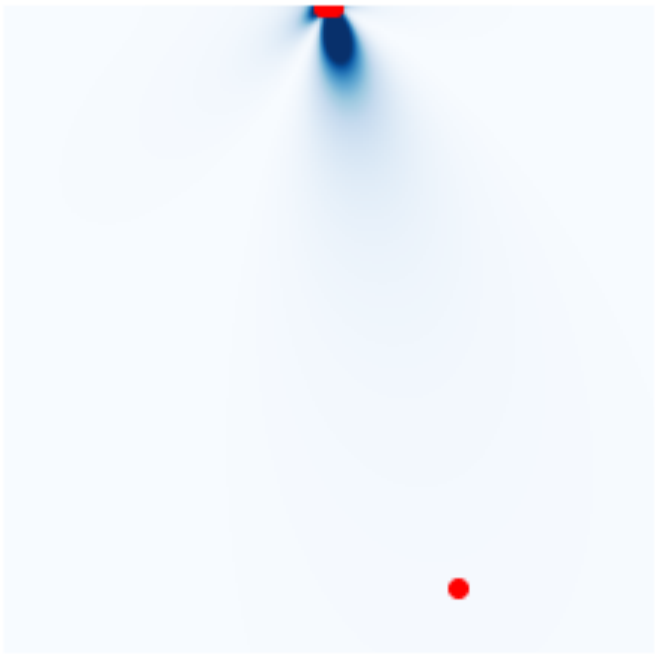
Beamforming ability is a function of the number of wavelengths the device spans

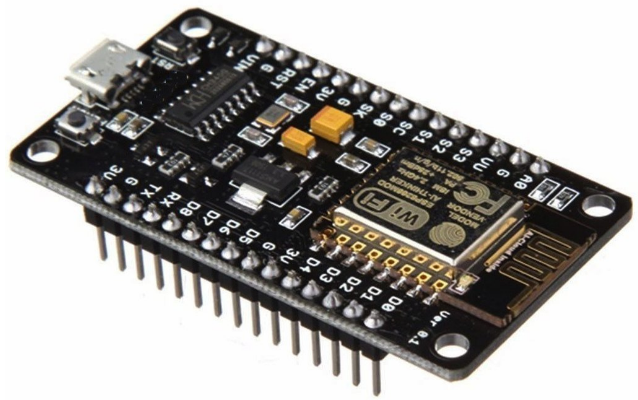
- Directional antennas can only be as directional as their size allows
- Squeezing more antennas into a smaller space doesn’t help

$\approx 2\lambda$

$\approx 2\lambda$

< 10 Antennas





More antennas won’t fit in our devices

The environment is already big. Let’s put antennas there!


Ceiling
Walls
Carpets

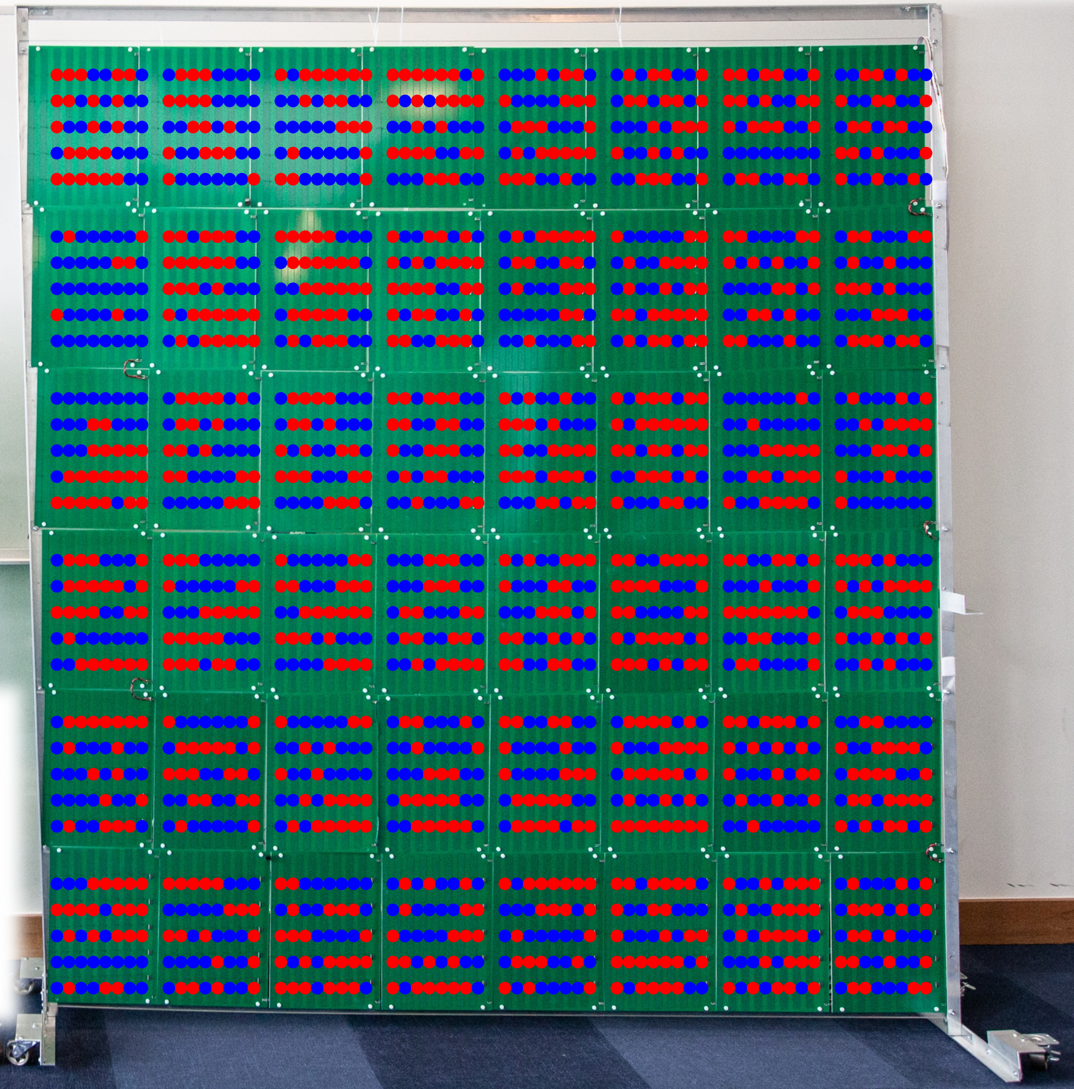
RFocus: An inexpensive “wallpaper” full of antennas

3200 antennas

- On - Reflective
- Off - Transparent

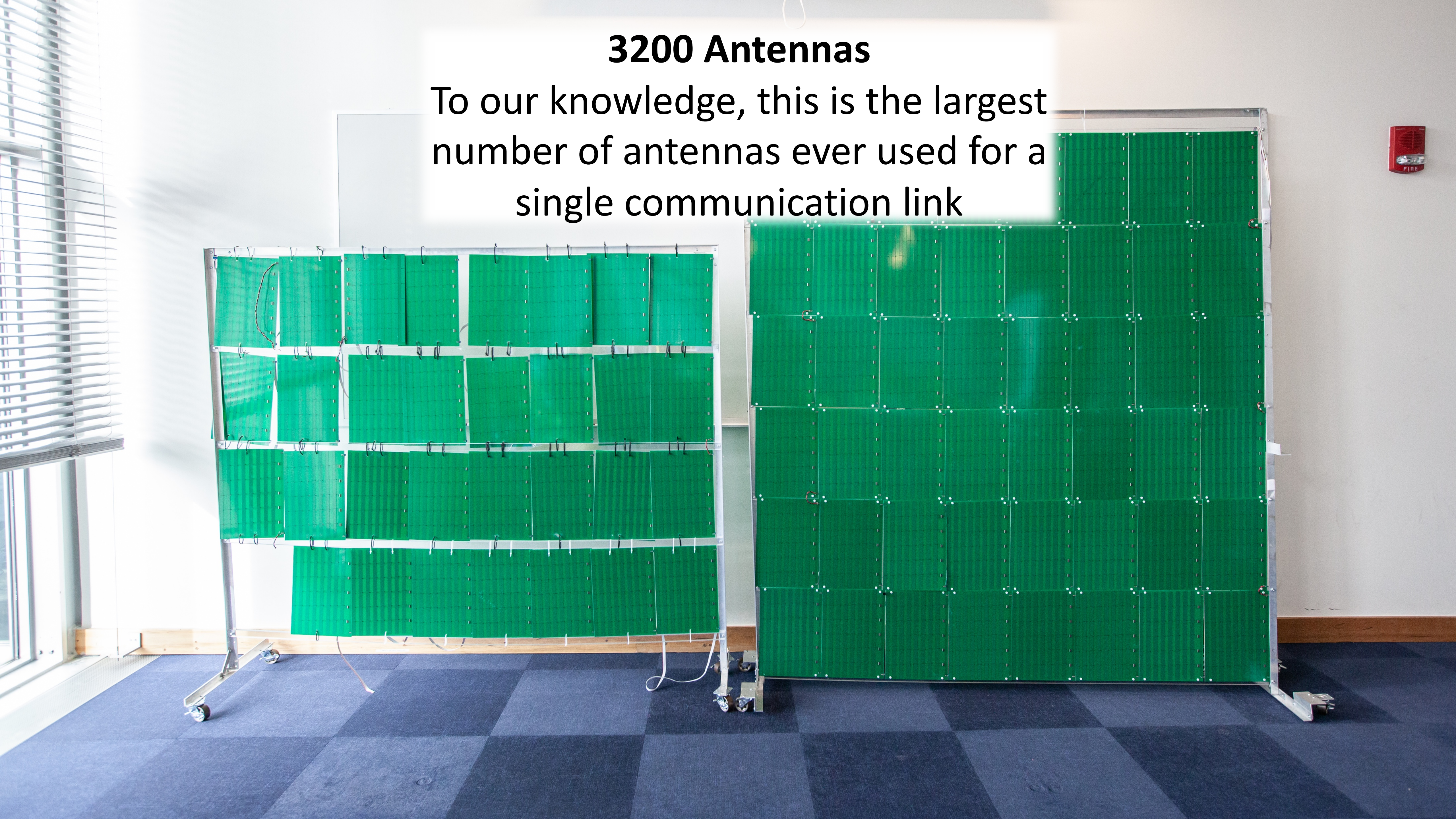
Passive: Does not emit any power

Only controls how it reflects radio (like an RFID tag)

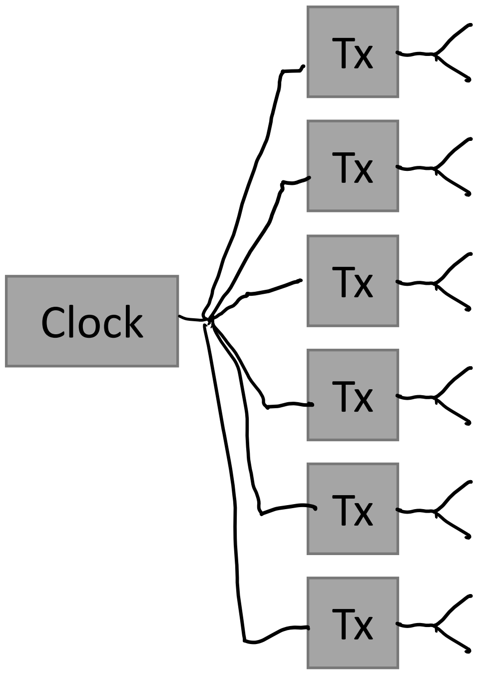


3200 Antennas

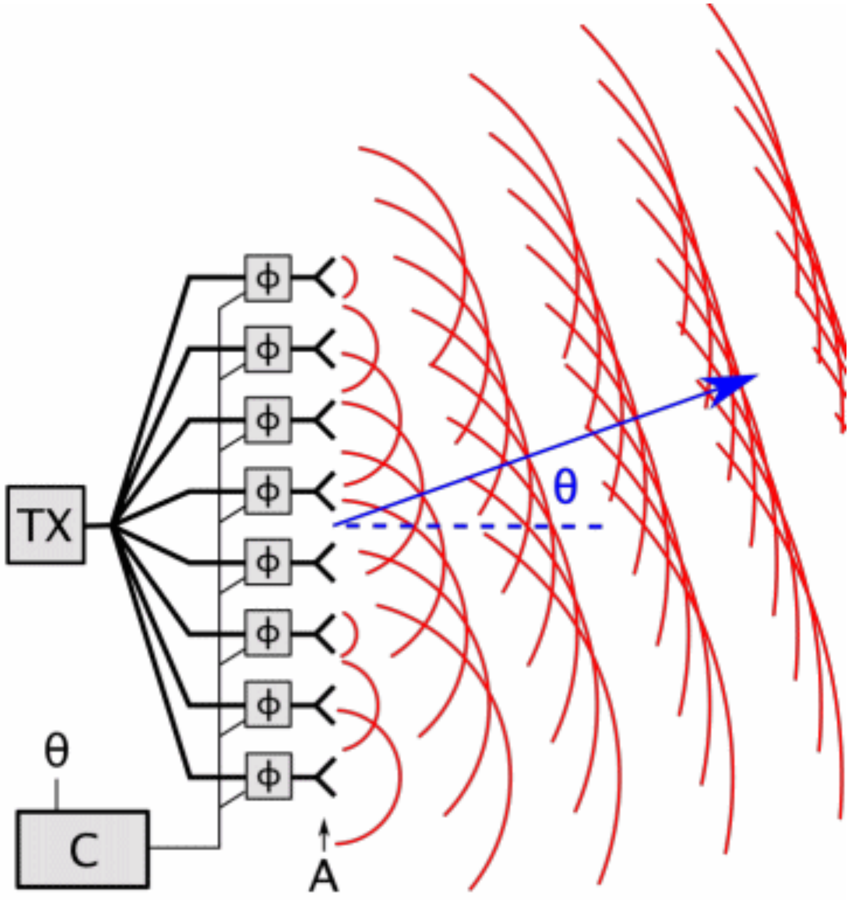
To our knowledge, this is the largest number of antennas ever used for a single communication link



Other ways to have >1 antenna



Independent RF chains

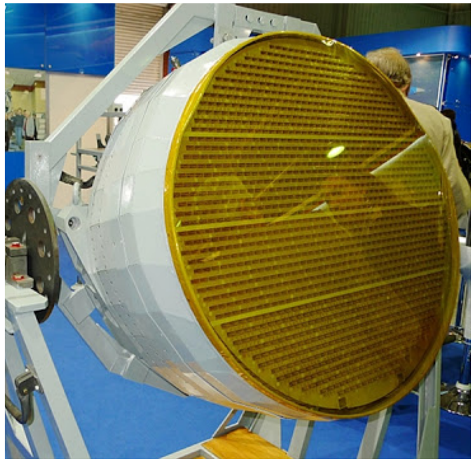


Phased Array

Why not phased arrays?

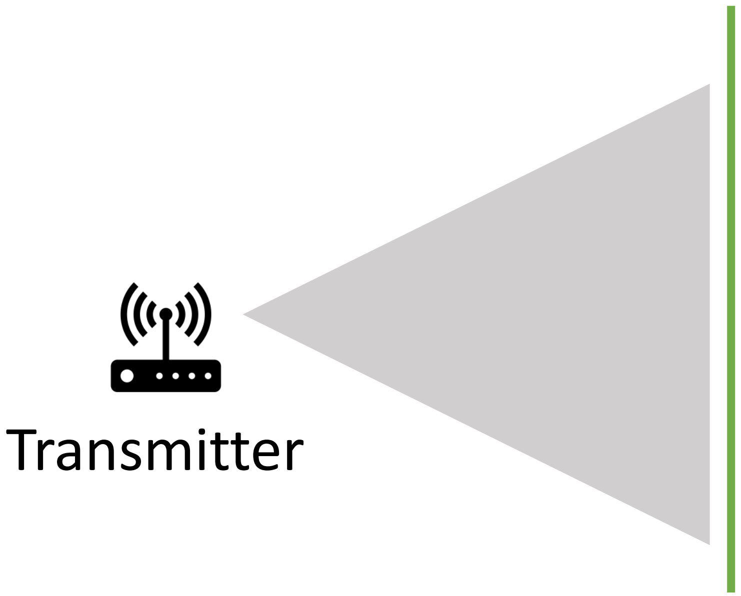
- Needs a splitter network to supply 1000s of antennas.
  - Coax cables or waveguides: expensive and bulky
  - PCB trace transmission line: lossy
  - Cannot be paper thin
- RFocus has a nicer deployment model
  - Endpoints need not be connected to RFocus
  - Allows RFocus to be pre-embedded in the environment. It can even be sold as disconnected pieces, e.g. in carpet squares
  - Currently RFocus’ antenna switches are controlled using (low-speed) wires
In the future, they can be powered and controlled wirelessly like RFID tags

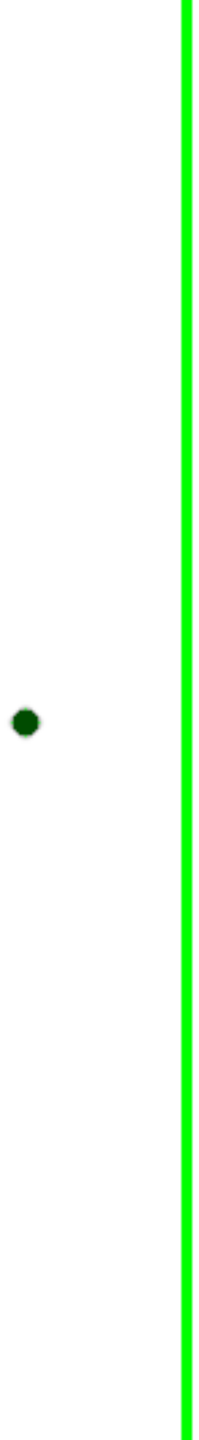
Radars use large phased arrays today



RFocus is a phased array

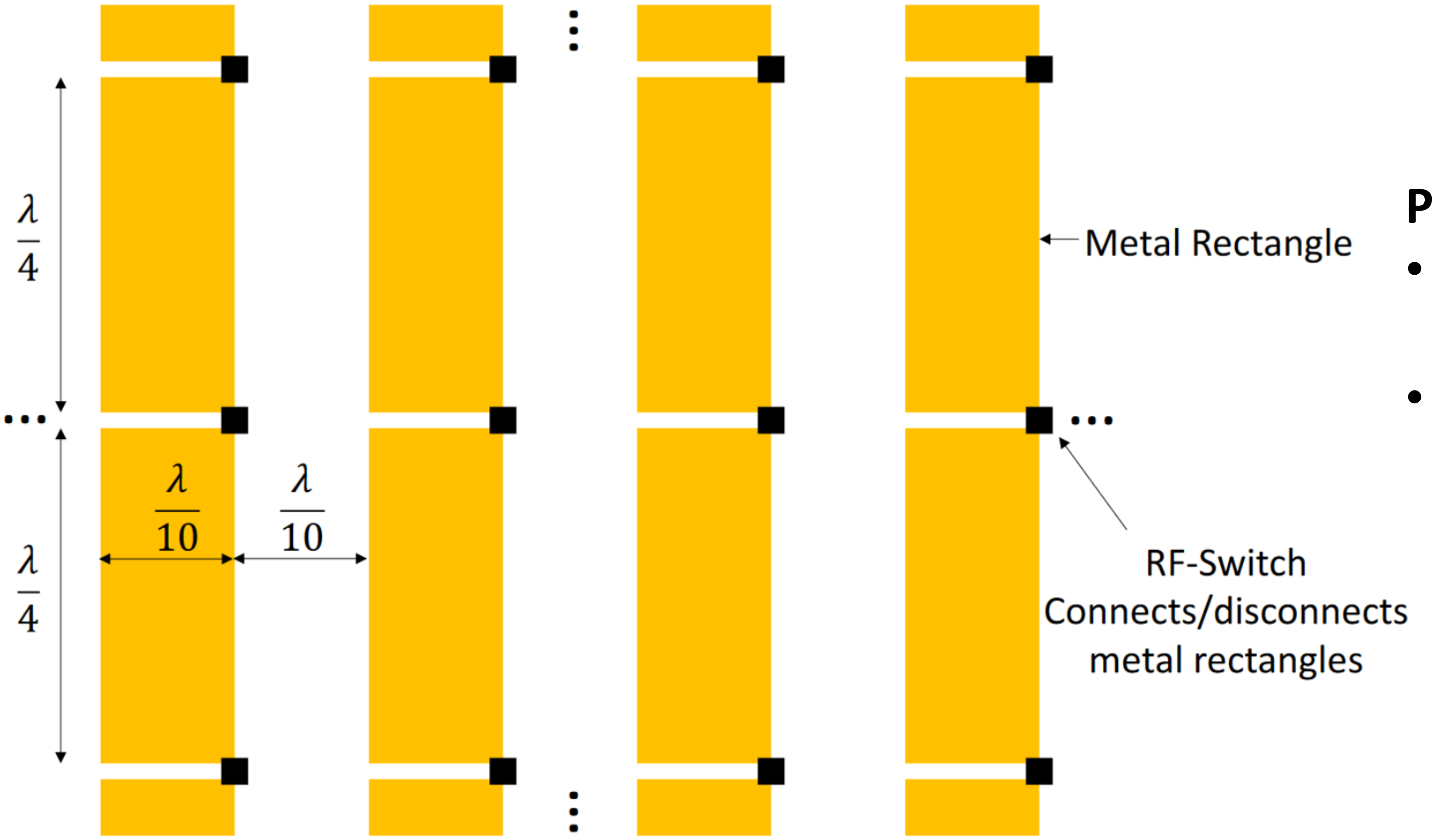
- RFocus is a phased array that uses the air as a splitter network
- At least one of the transmitter and the receiver needs to be close to the surface
- In our case, the loss is 10 dB. This is comparable to a PCB trace transmission line





Target

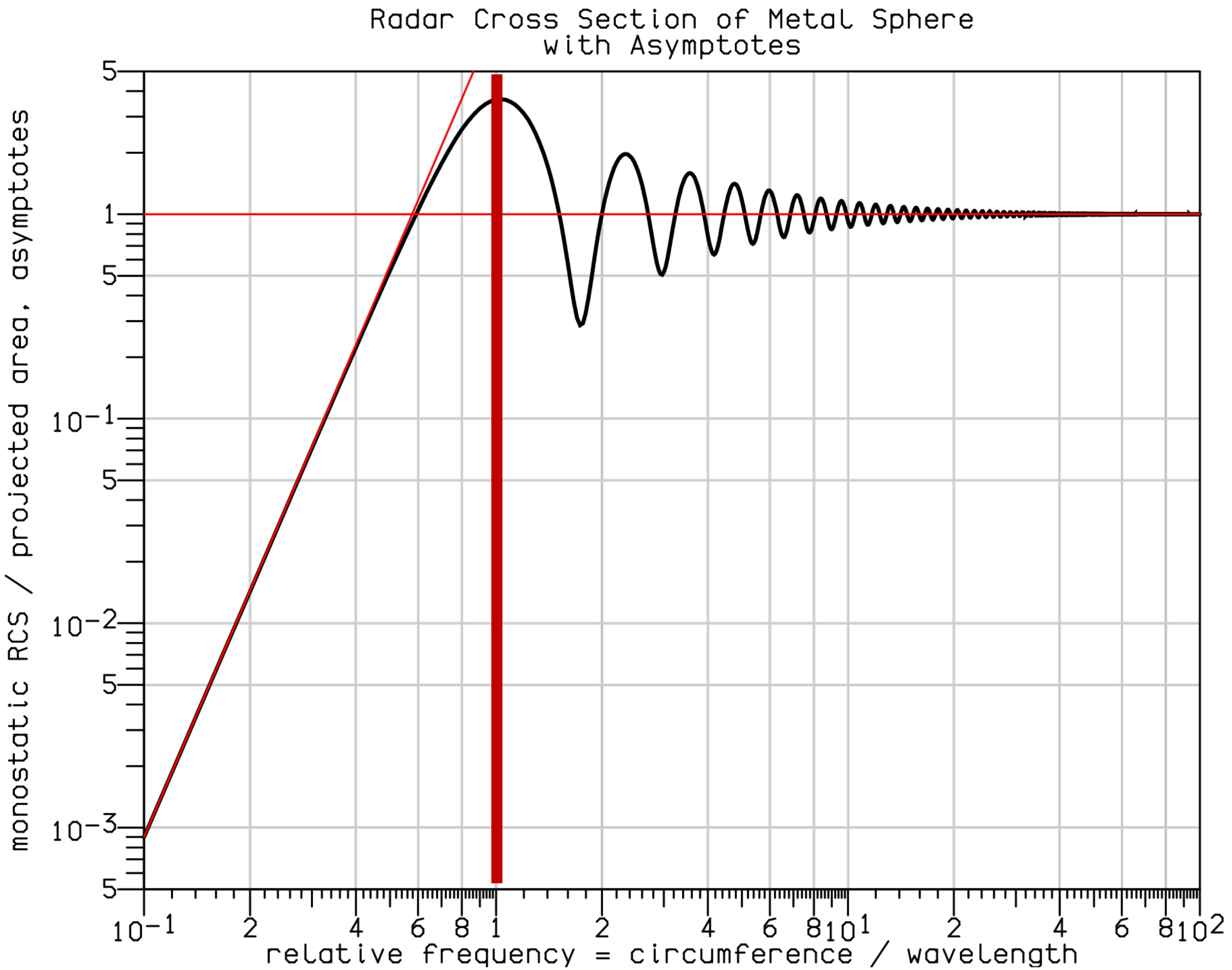
How RFocus works



Principles of Operation:

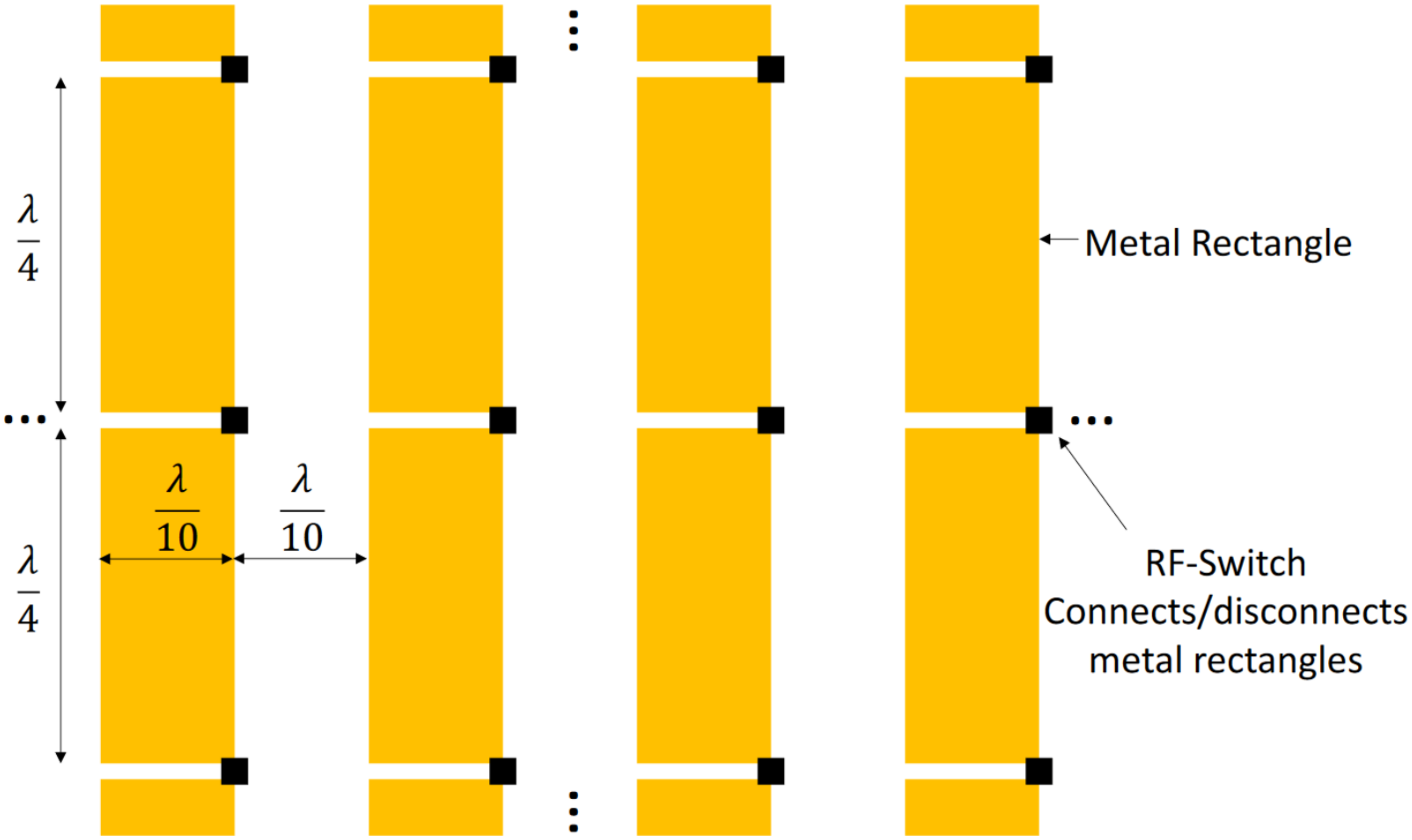
- Small objects are "invisible" to radio
- Small holes in a sheet of metal are ignored

Small objects are "invisible" to radio



Mie scattering from a sphere

How Rfocus works

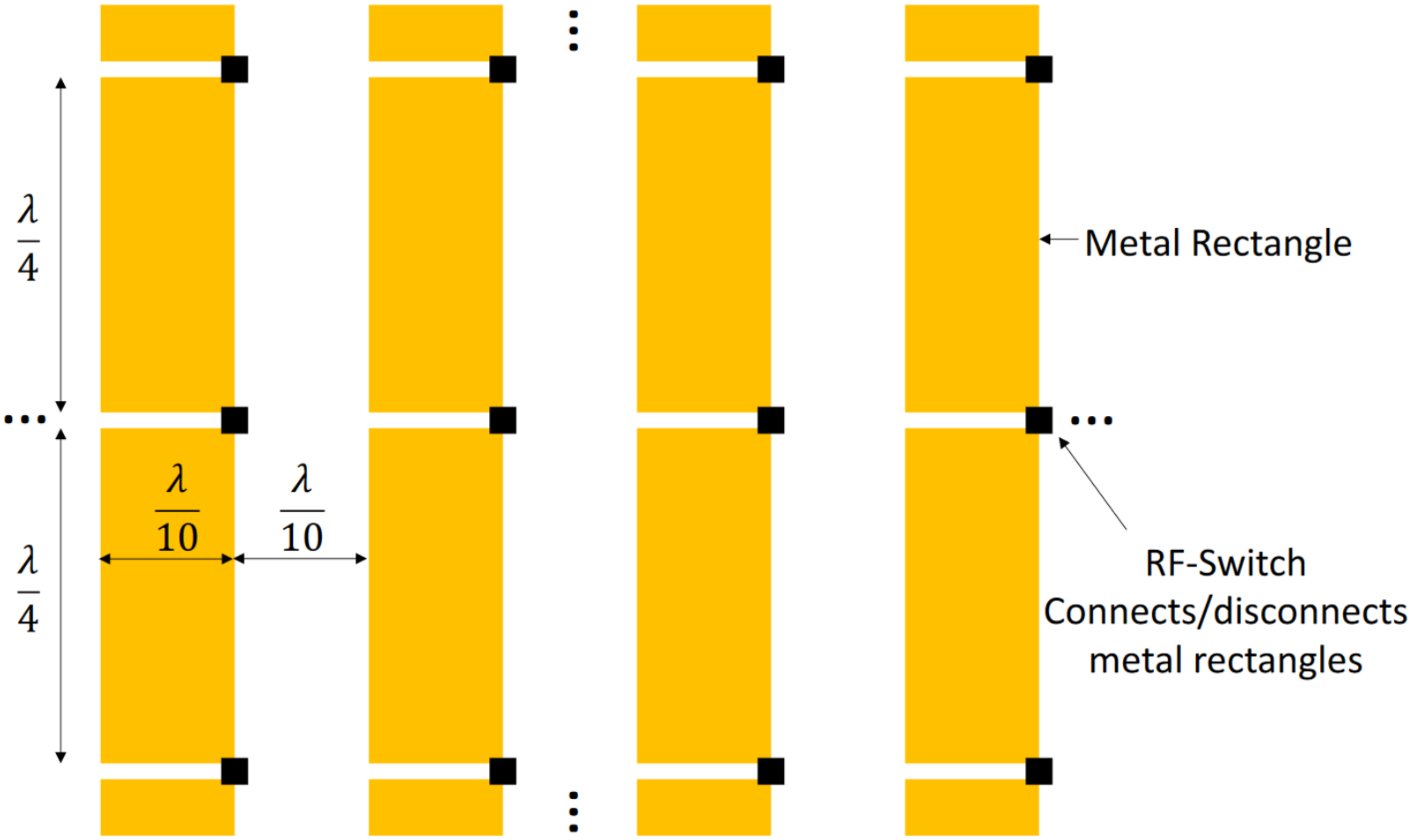


When connected, the pieces of metal are larger

When disconnected, it is (more) transparent

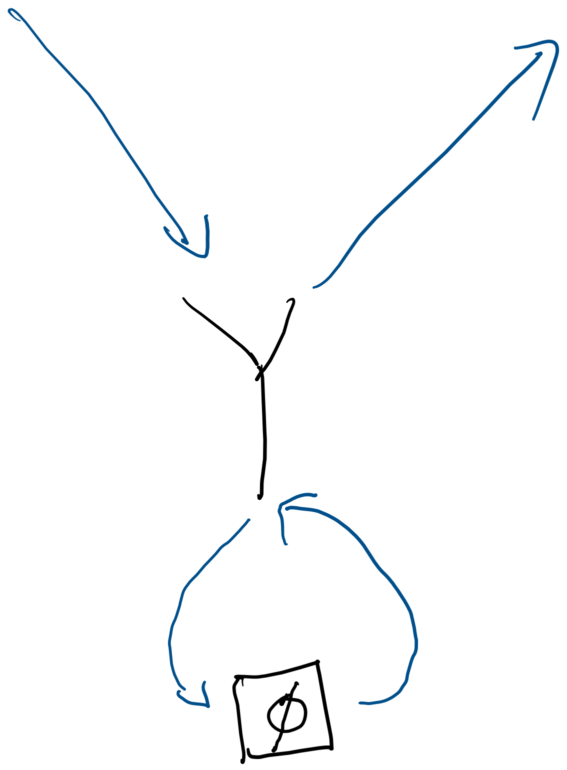
Radio ignores small holes

How Rfocus works



When adjacent columns are activated, the holes cease to matter

2-state vs full phase shifter



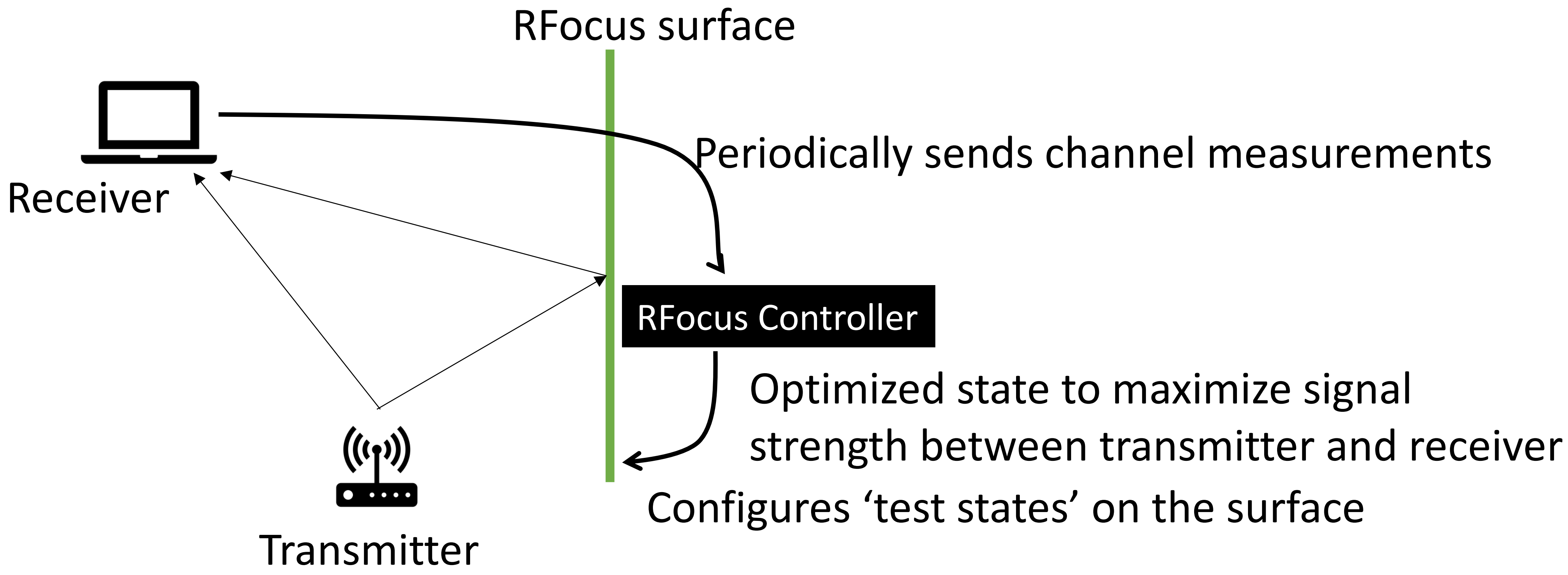
Phase shifter

Compare to a full phase shifter, RFocus gets $\frac{1}{\pi^2}$ of the signal strength improvement

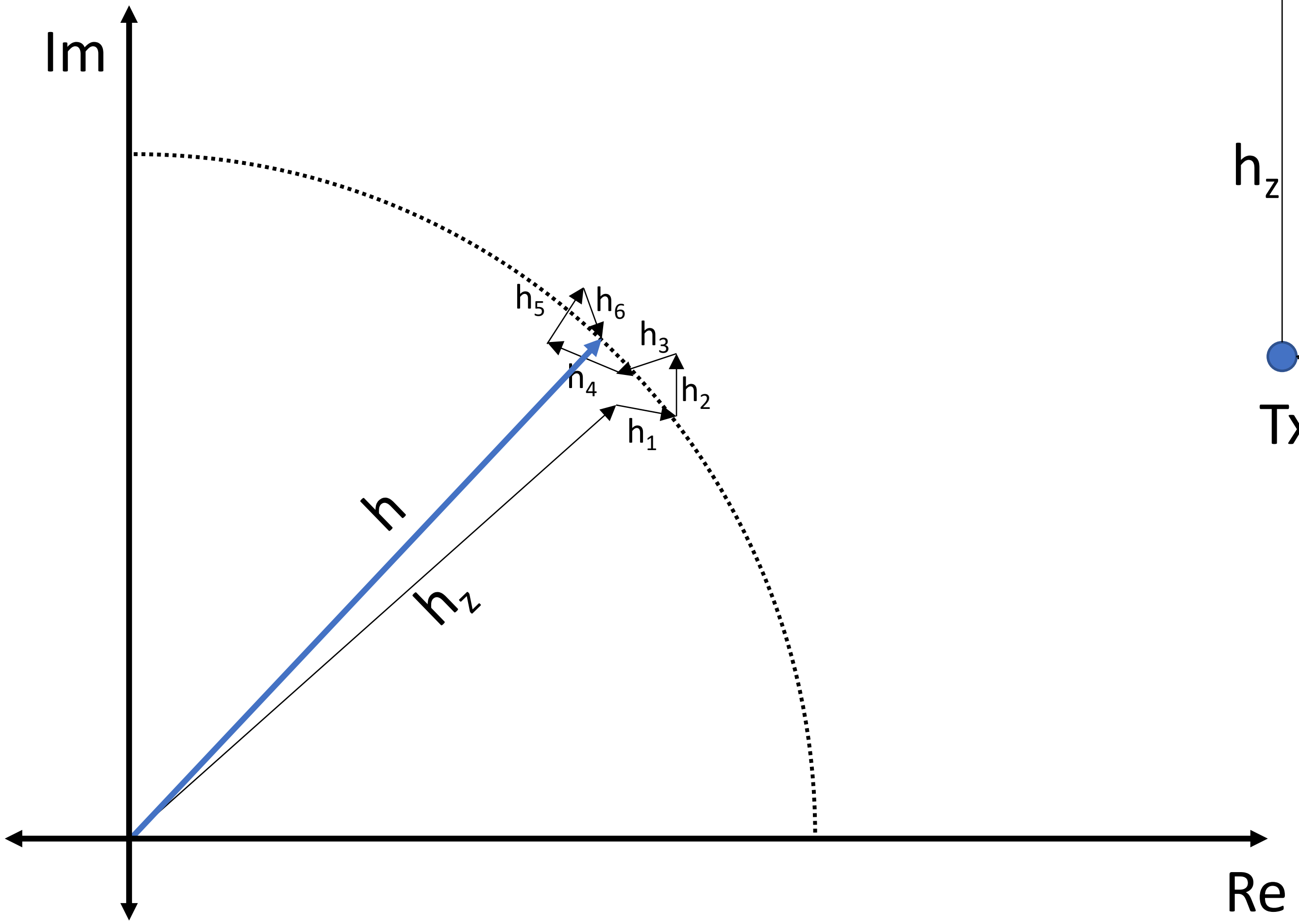
Goal: Increase Signal Strength

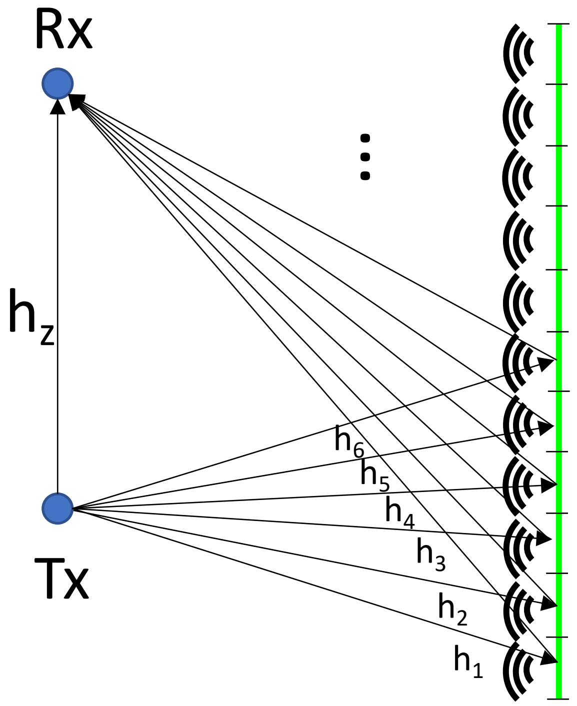
Cellular Networks | WiFi | IoT Sensor Networks

System Architecture

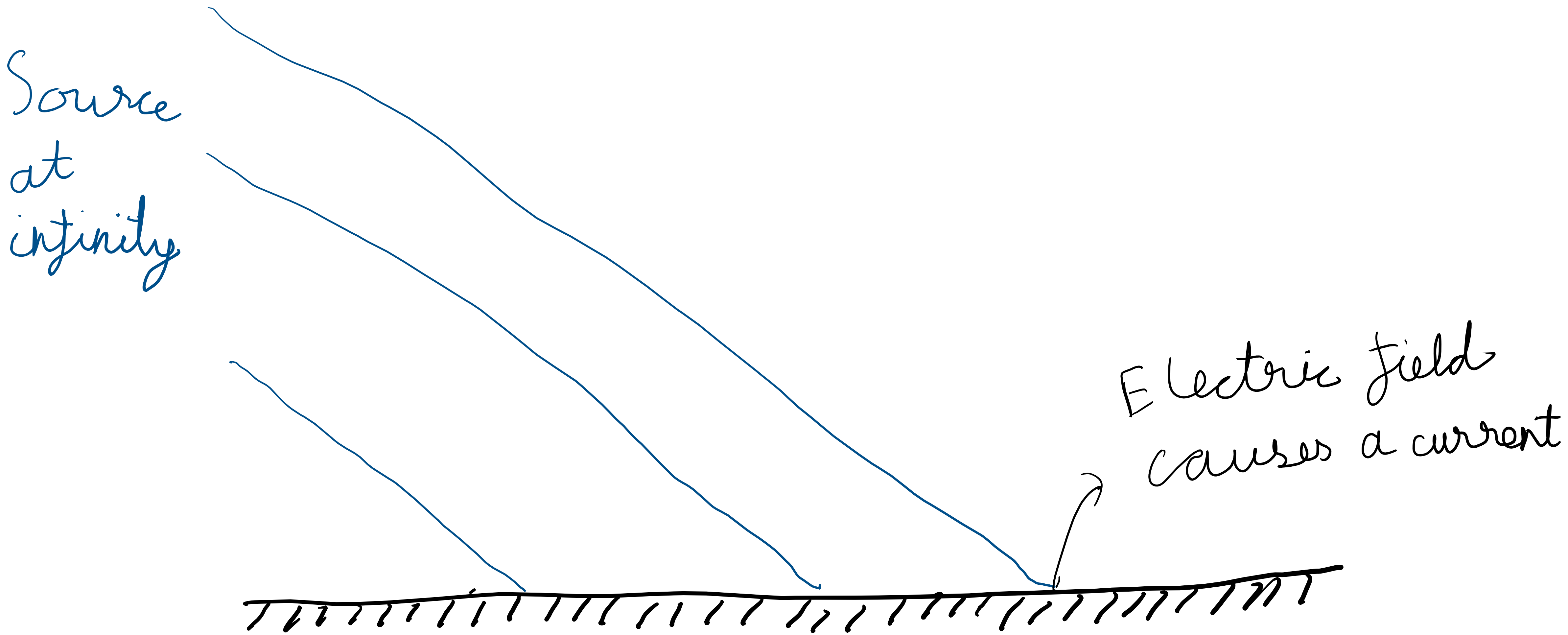


Reflection from a wall





Reflection from a flat surface (mirror)



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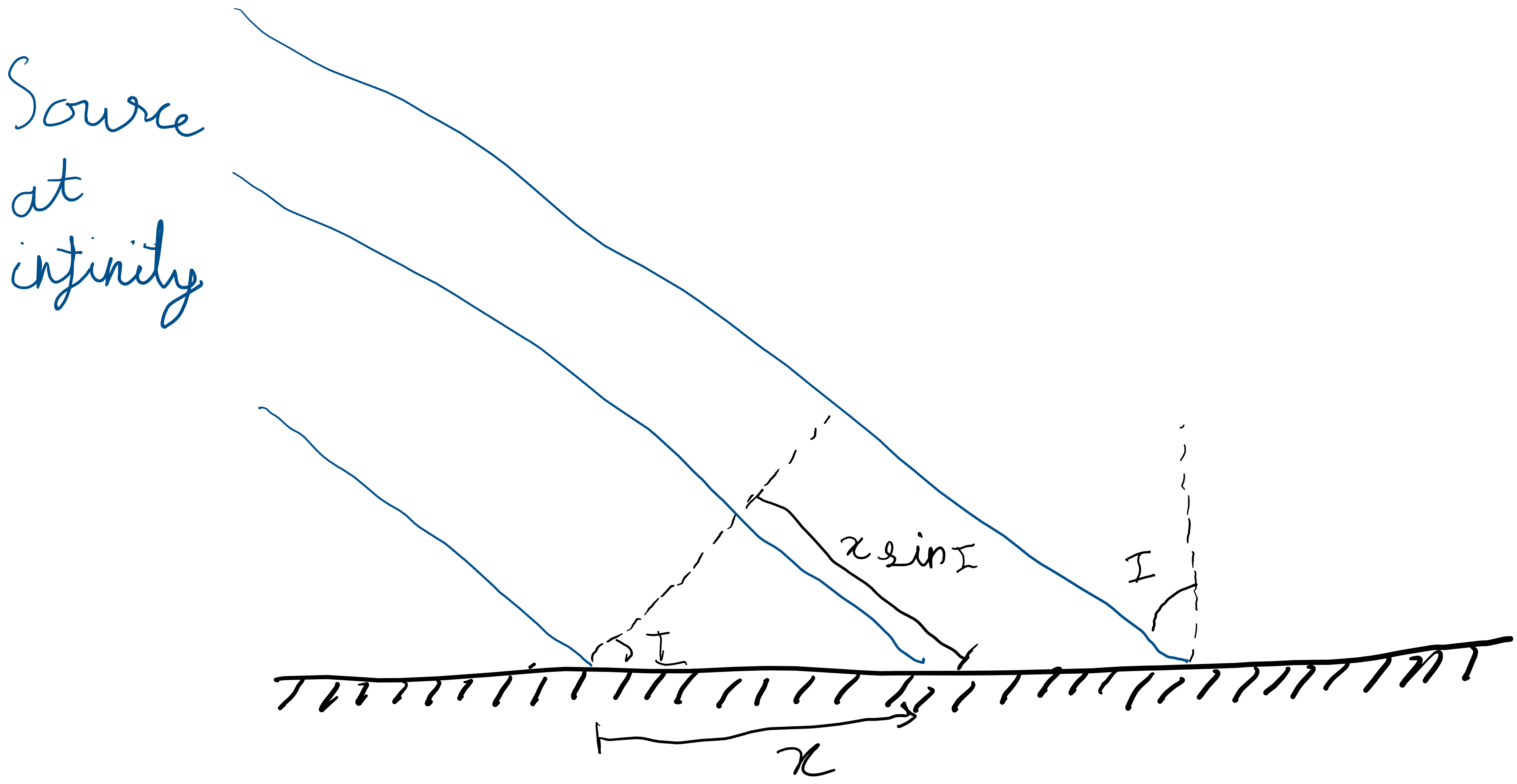

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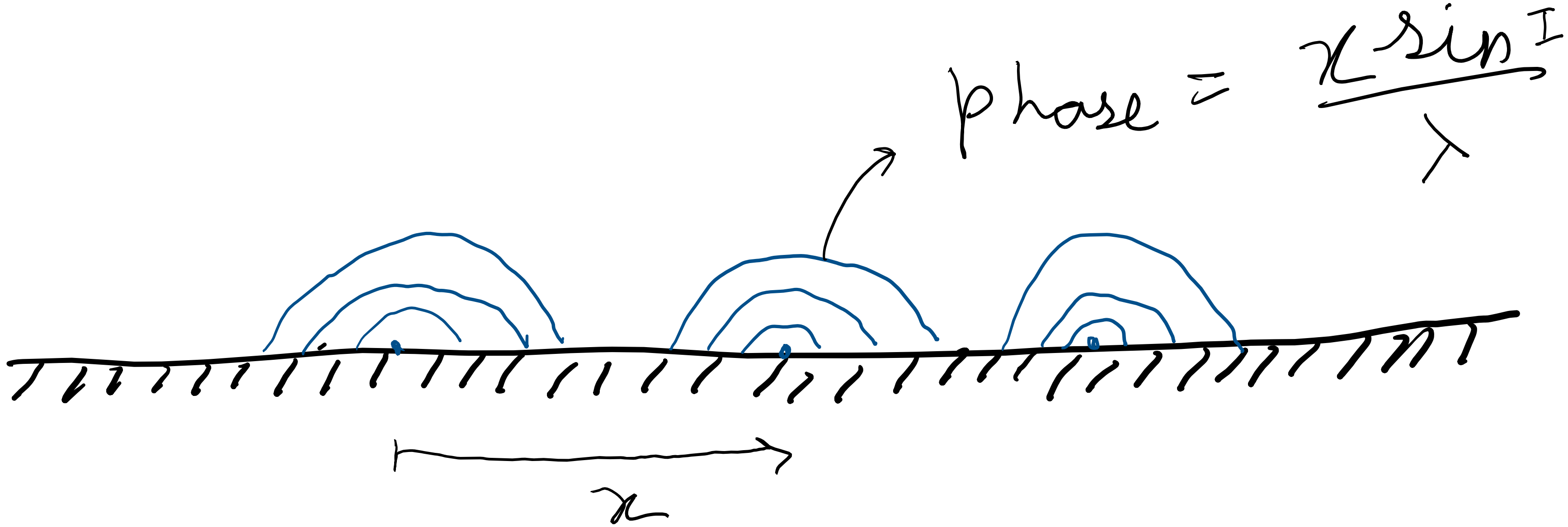

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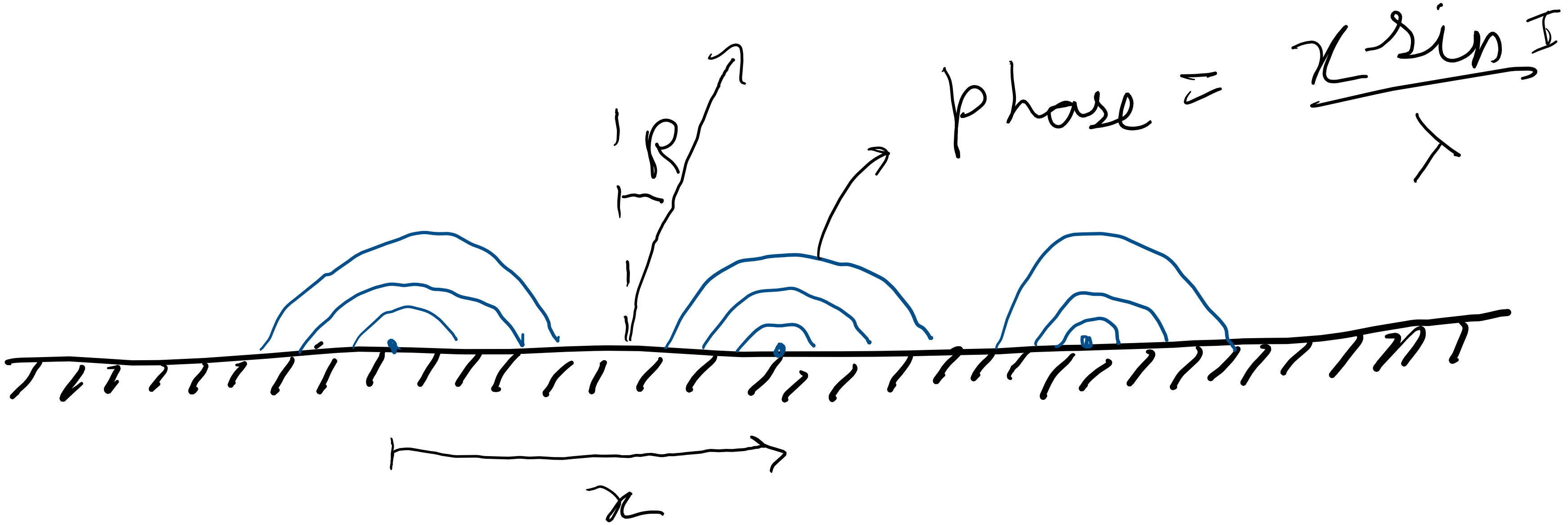
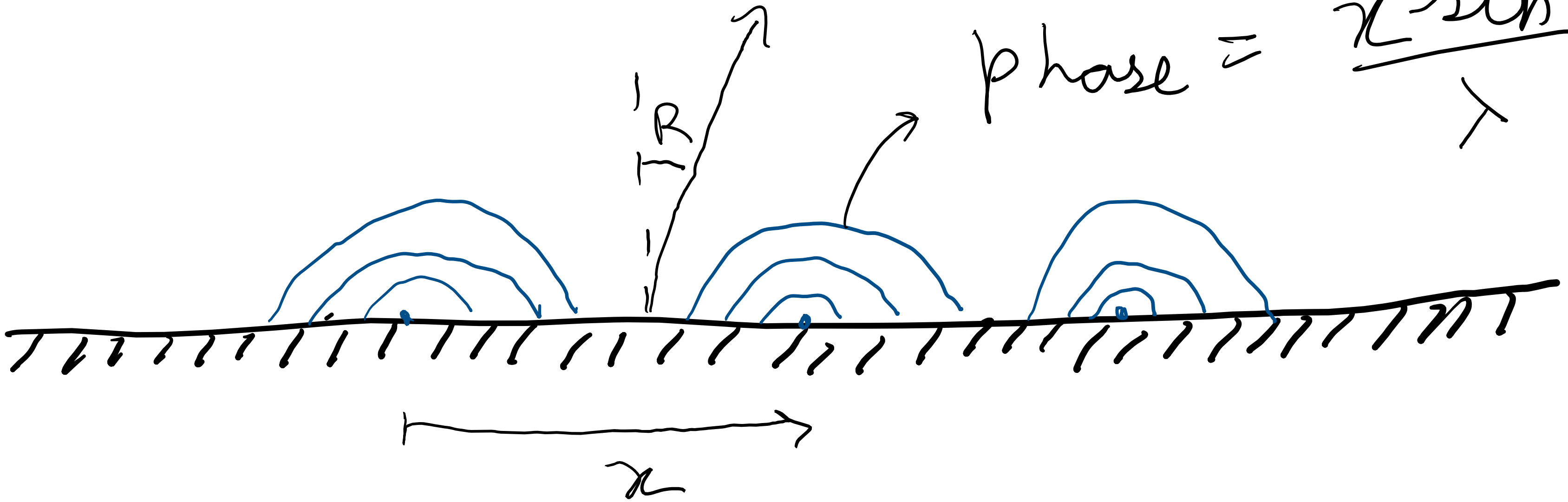


Reflection from a flat surface (mirror)

$$R(\phi) = \int_{-\infty}^{\infty} e^{-jx\sin R/\lambda}\, e^{jx\sin I/\lambda} \, . \, dx$$

$$= 0 \text{ unless } I = R$$

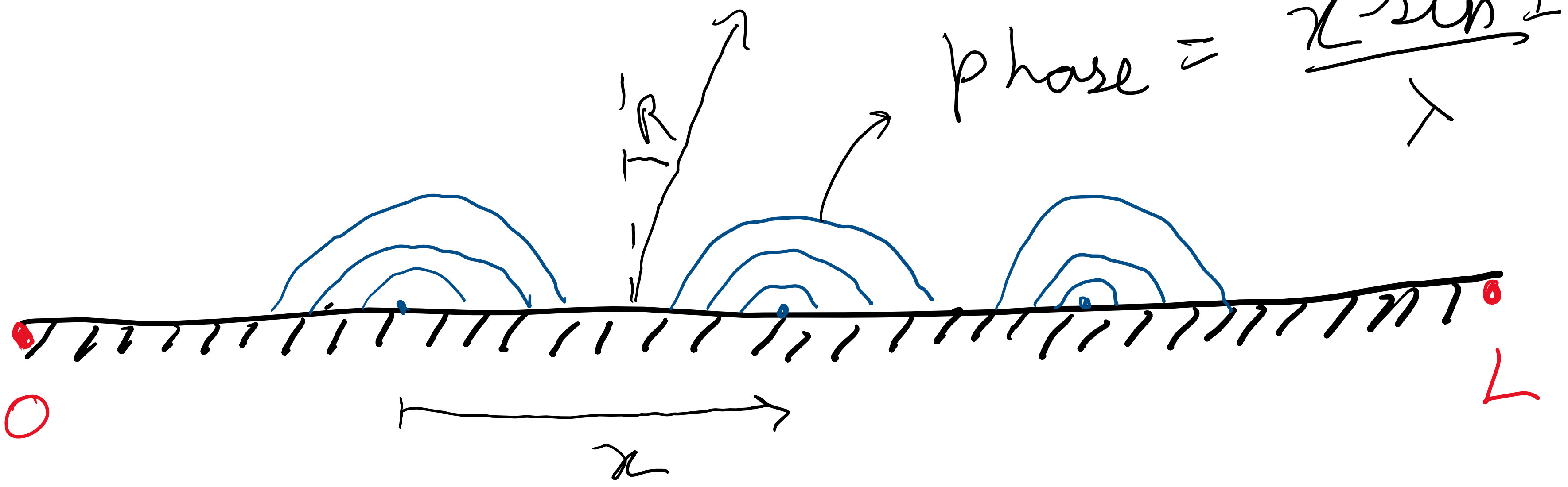
$$\text{phase} = \frac{x \sin \theta}{\lambda}$$



Reflection from a flat surface (mirror)

$$R(\phi) = \int_0^L e^{-jx\sin R/\lambda}\, e^{jx\sin I/\lambda}\, dx$$

$$\approx L - O\left((I-R)^2\right)$$



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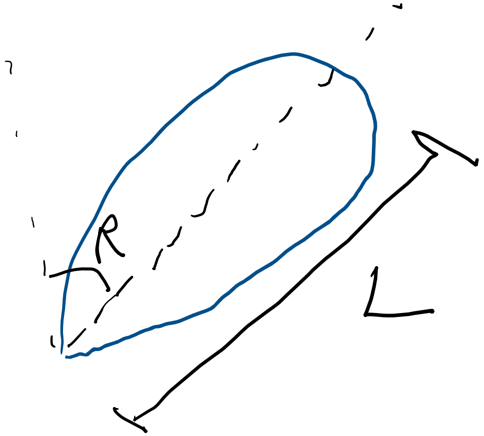

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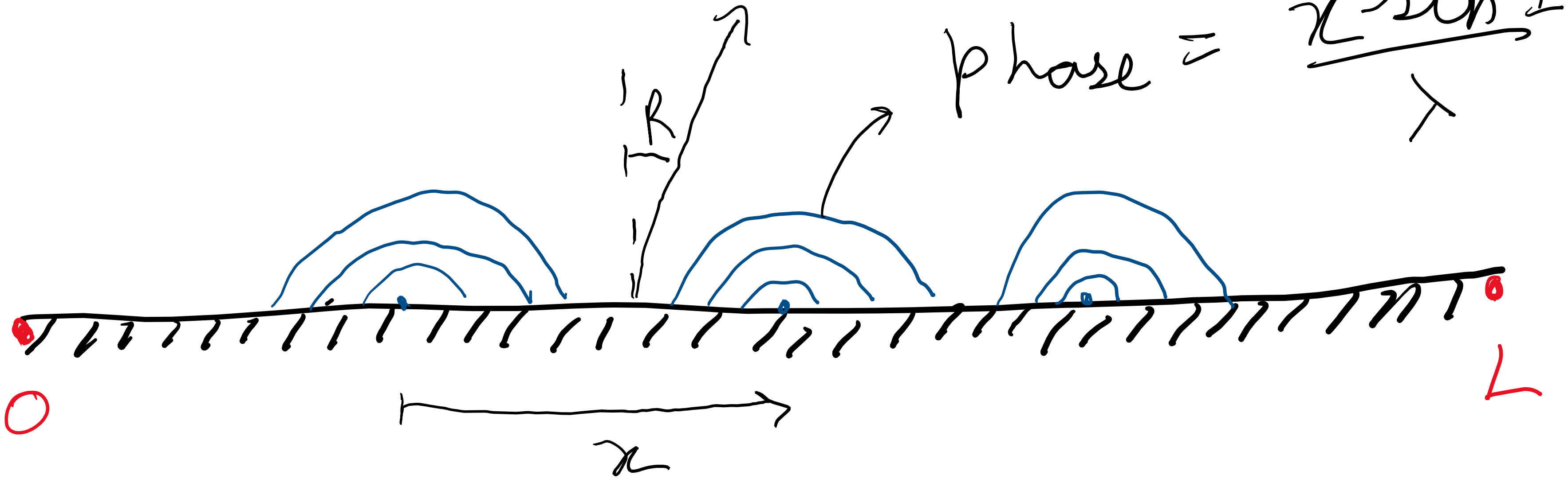

Reflection from a flat surface (mirror)

$$R(\phi) = \int_0^L e^{-jx\sin R/\lambda}\, e^{jx\sin I/\lambda} \cdot dx$$

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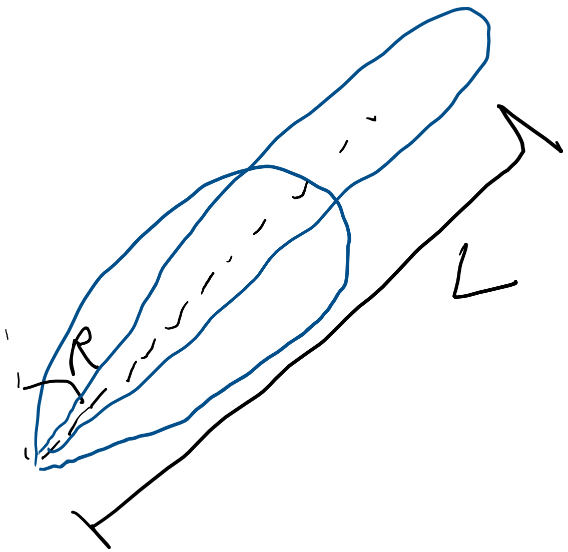

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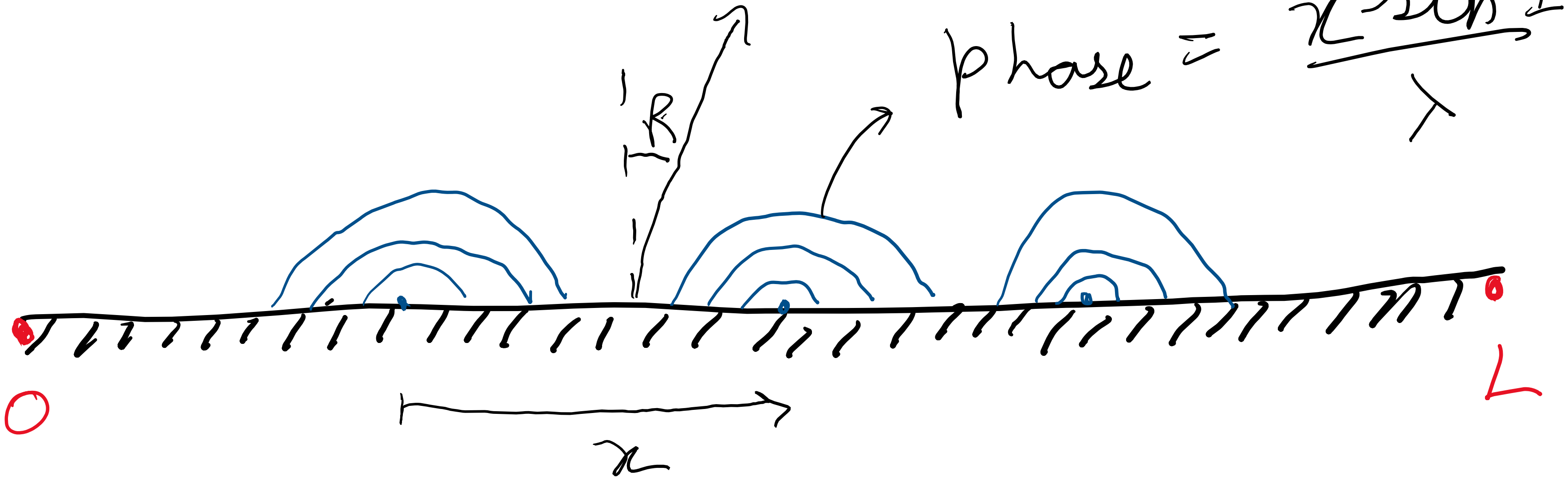
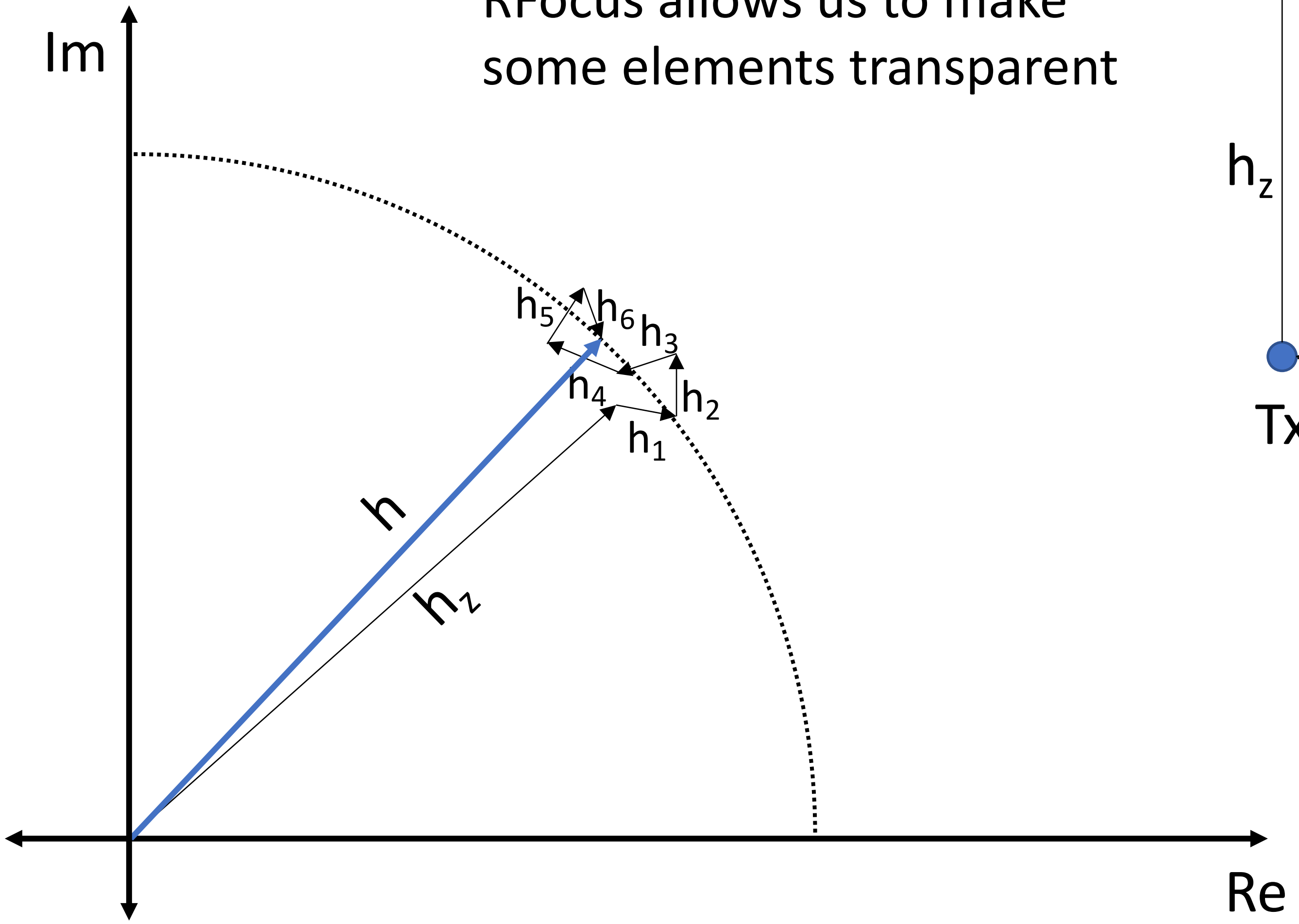
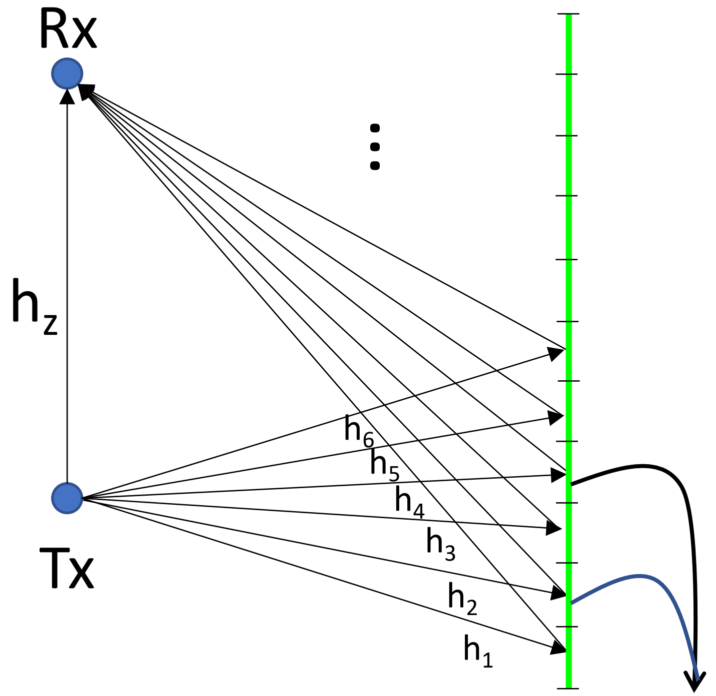


Improving the Reflection

RFocus allows us to make some elements transparent





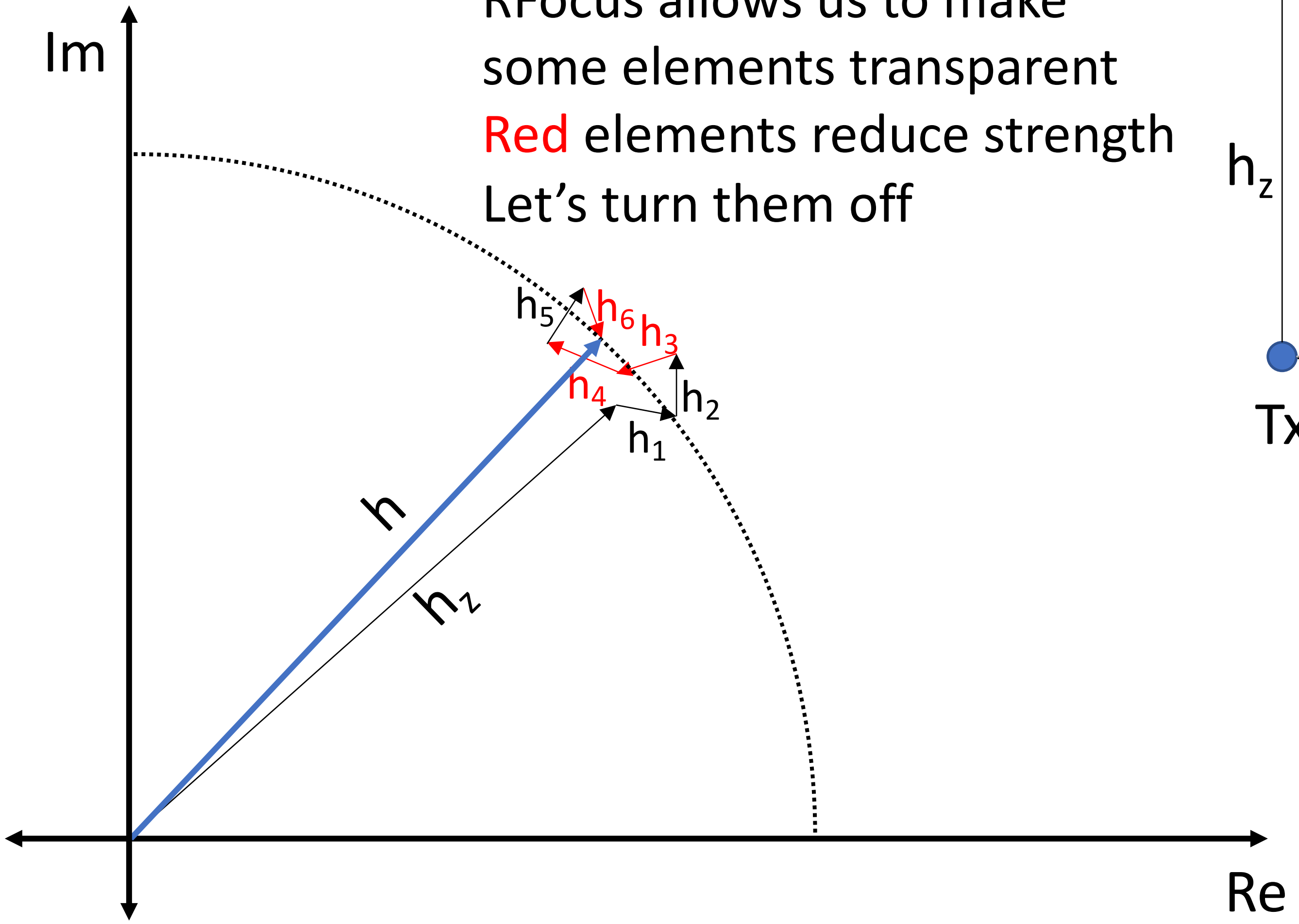
Antennas in RFocus

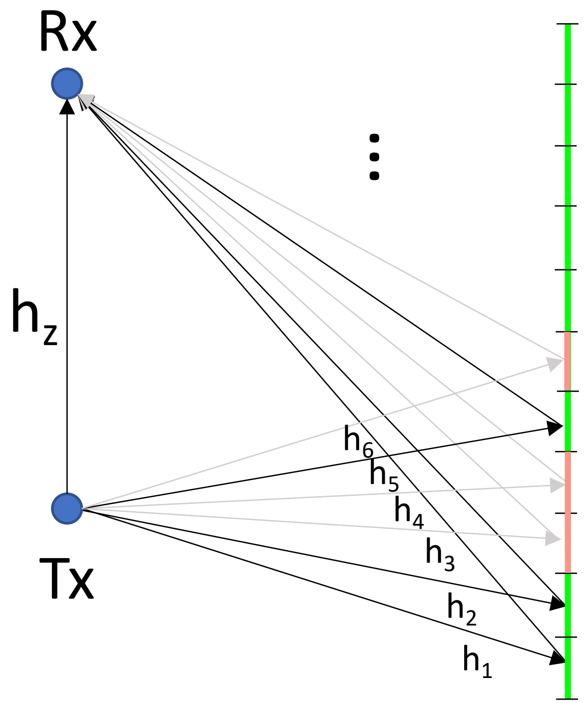
Improving the Reflection

RFocus allows us to make some elements transparent

Red elements reduce strength

Let's turn them off





Improving the Reflection

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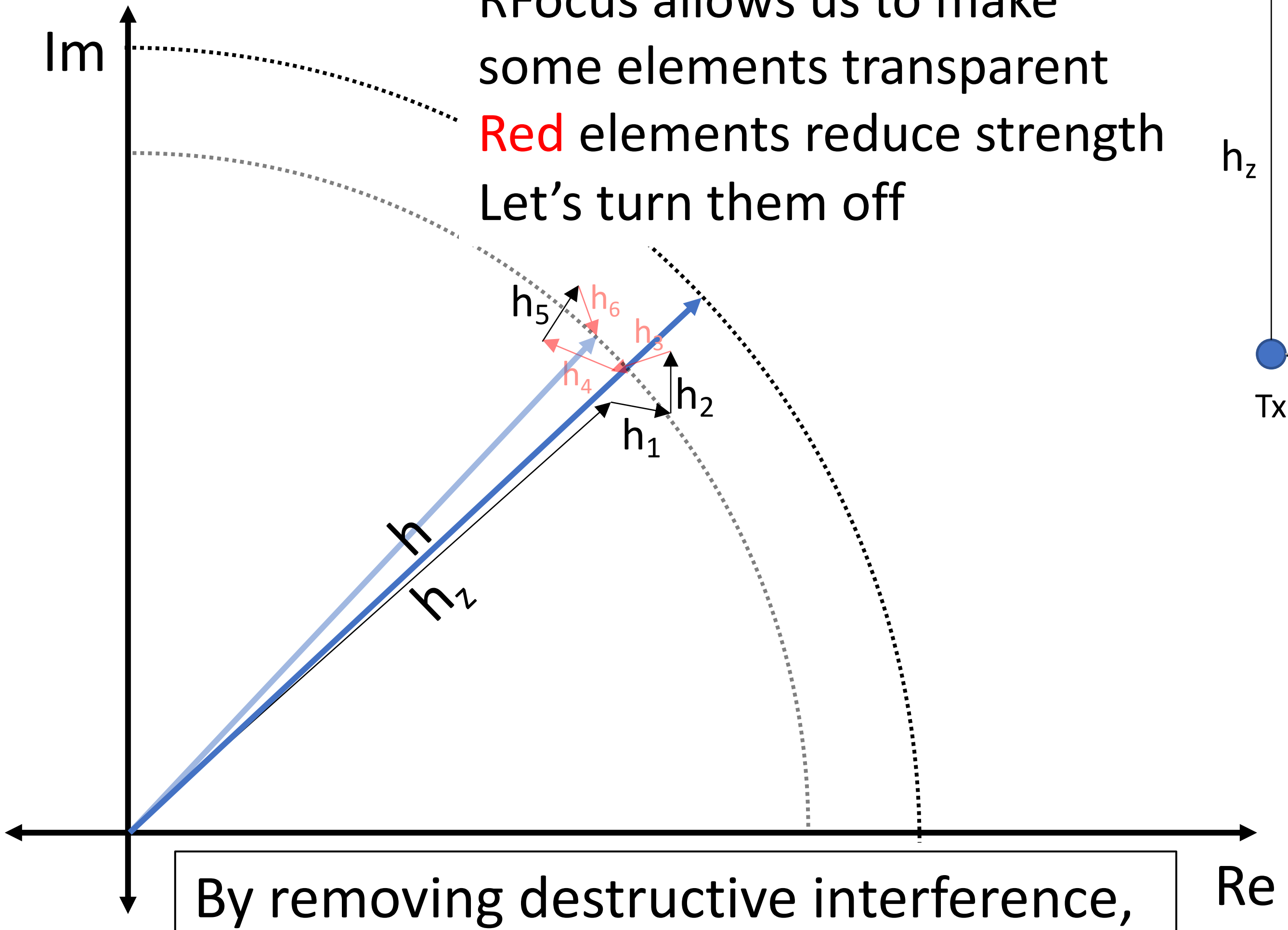
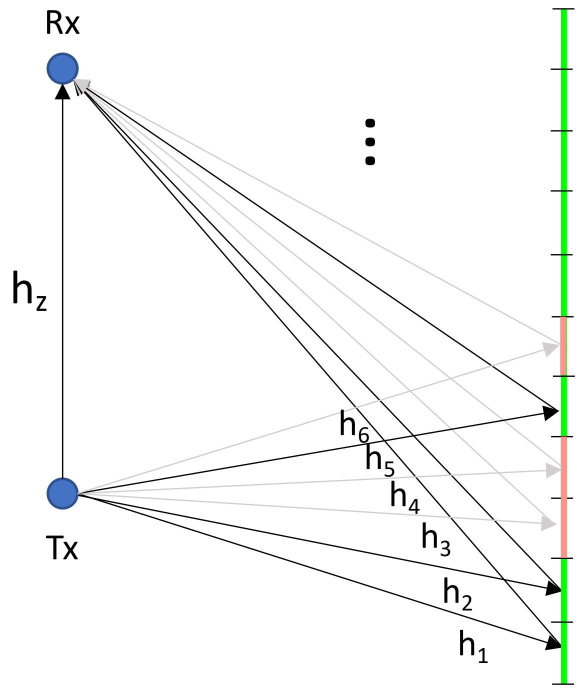
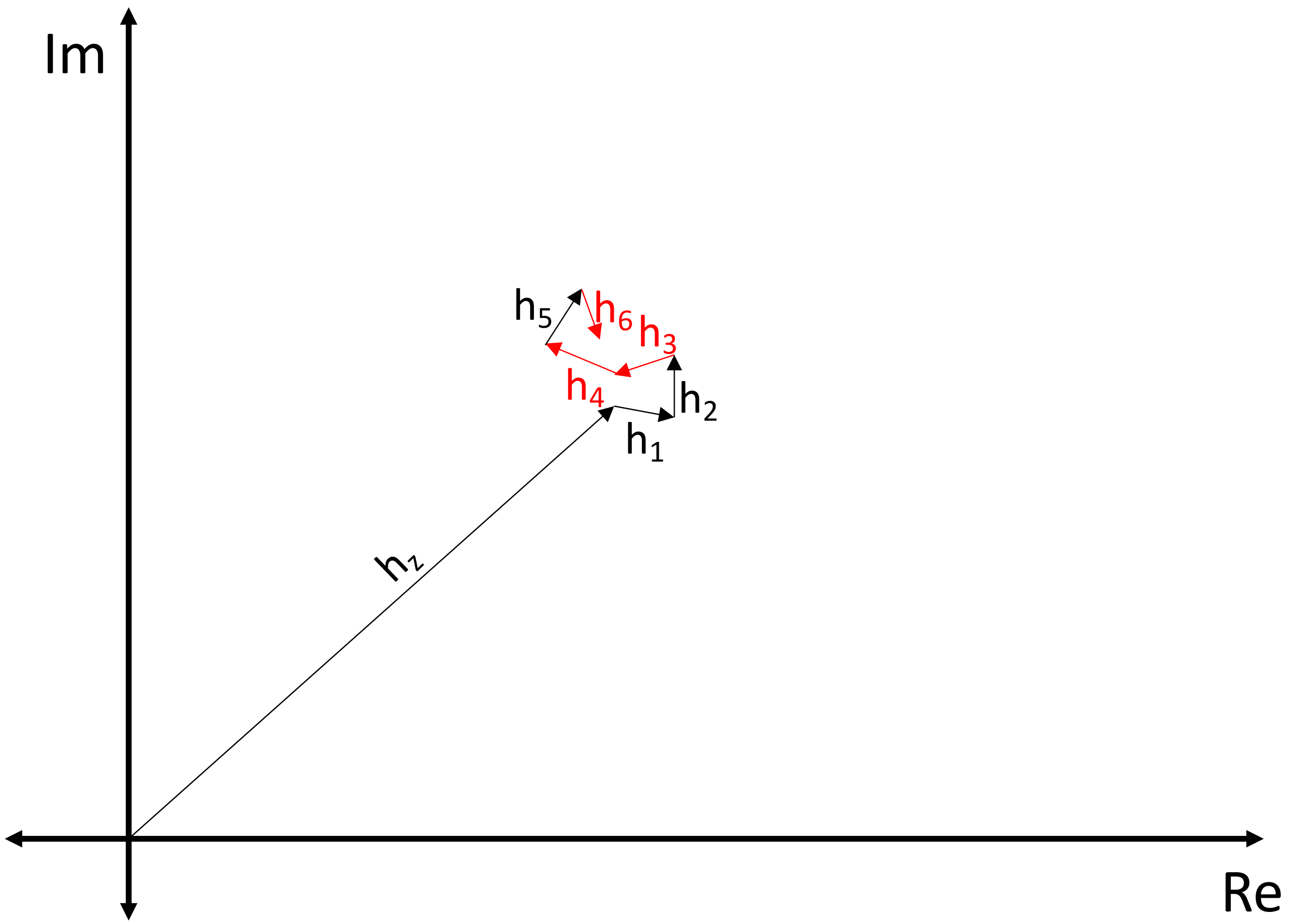


By removing destructive interference, we increase signal strength



Which antennas should we turn off?



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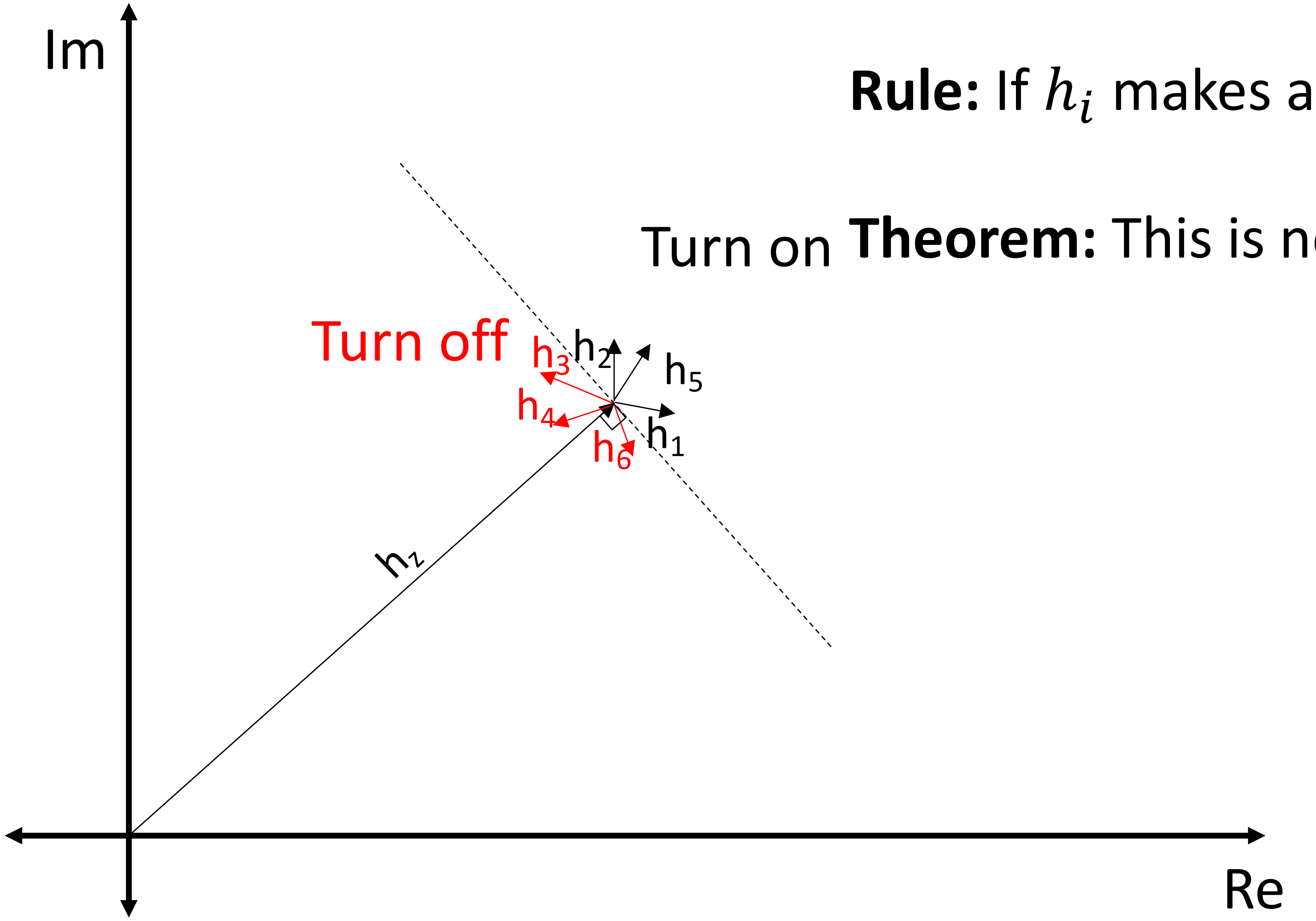
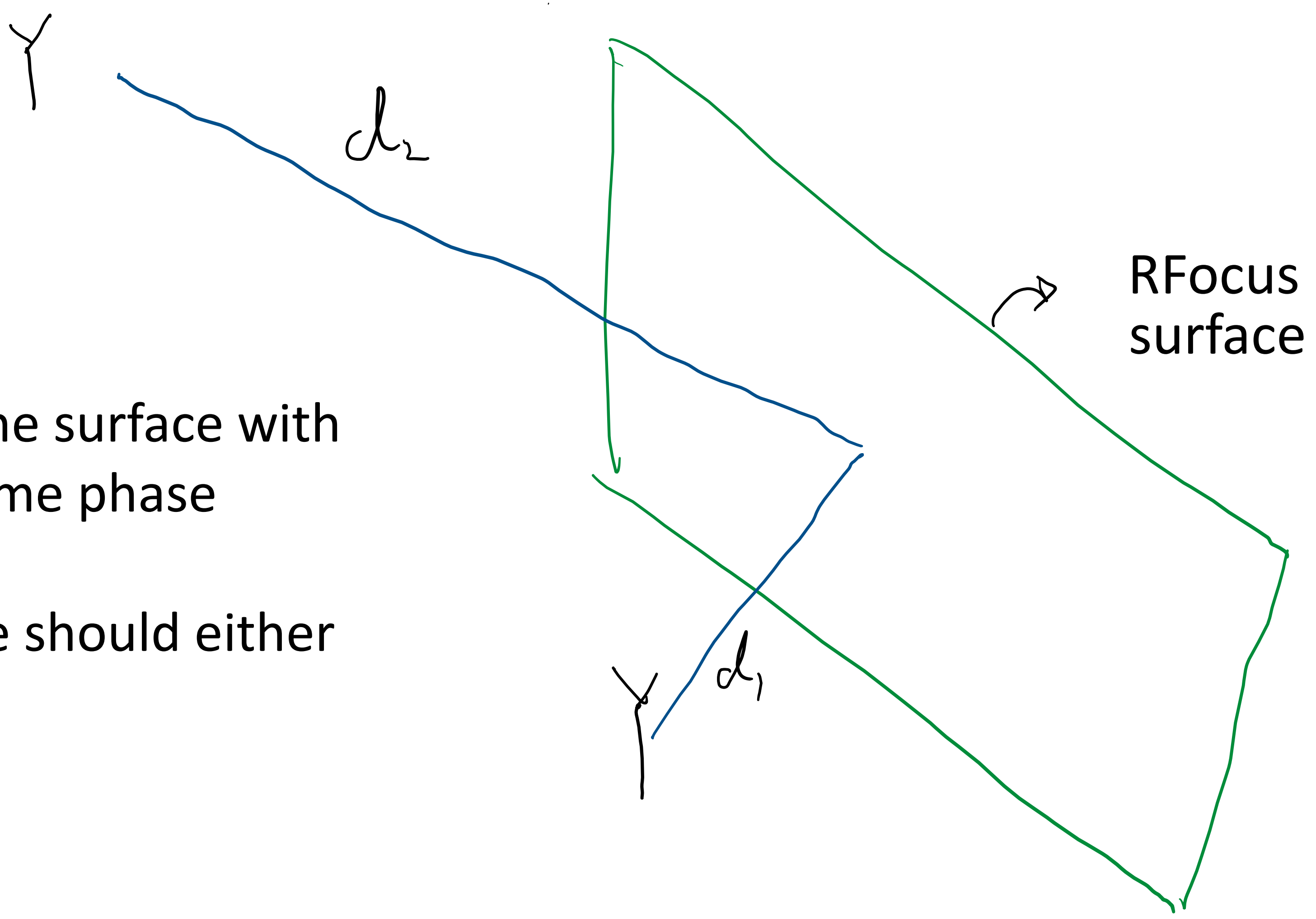


Rule: If h_i makes an acute angle with h_z, turn it on

Theorem: This is near optimal

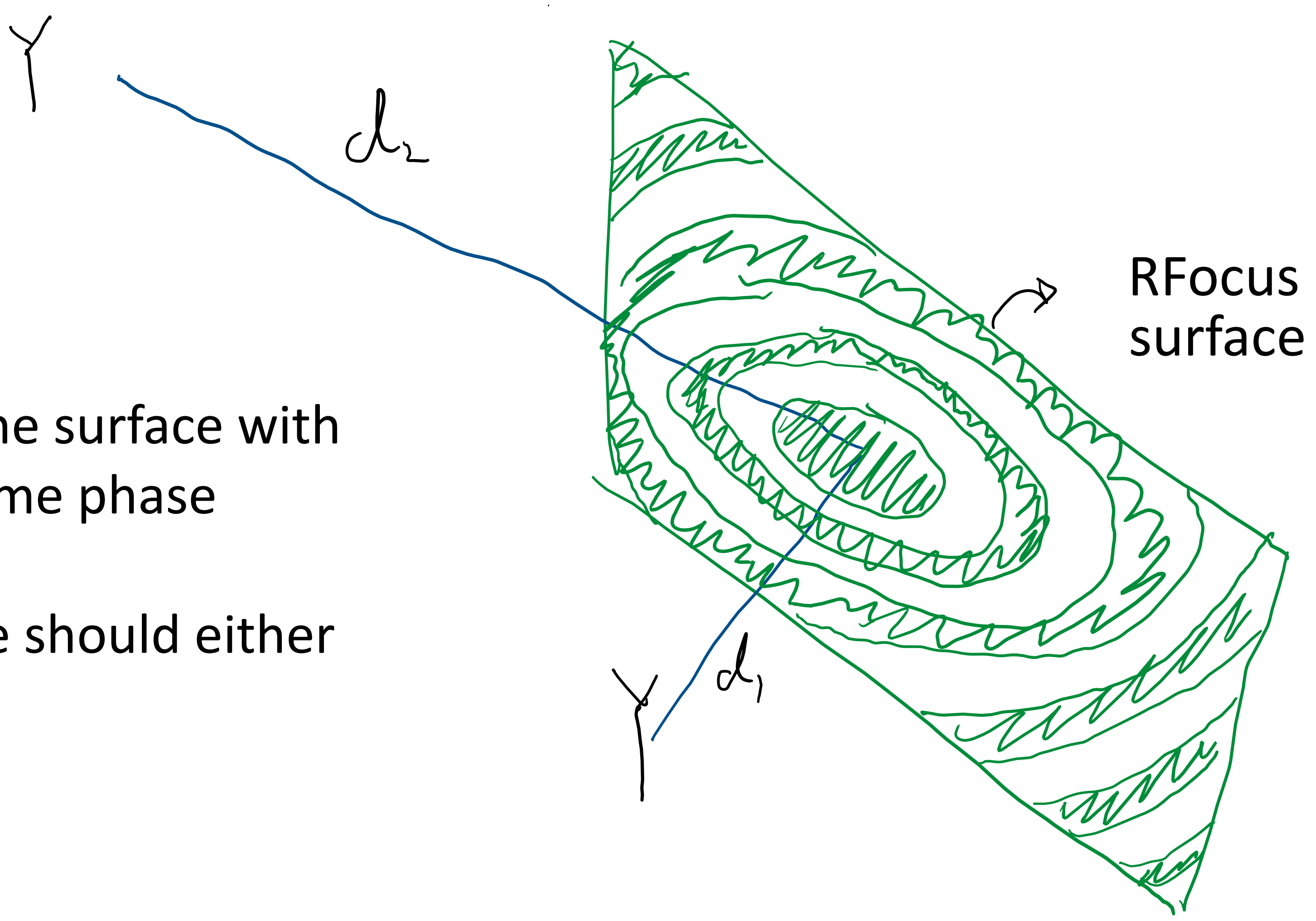
RFocus in empty space



The paths from all points on the surface with the same $d_1 + d_2$ have the same phase

All points with the same phase should either be on or off

RFocus in empty space



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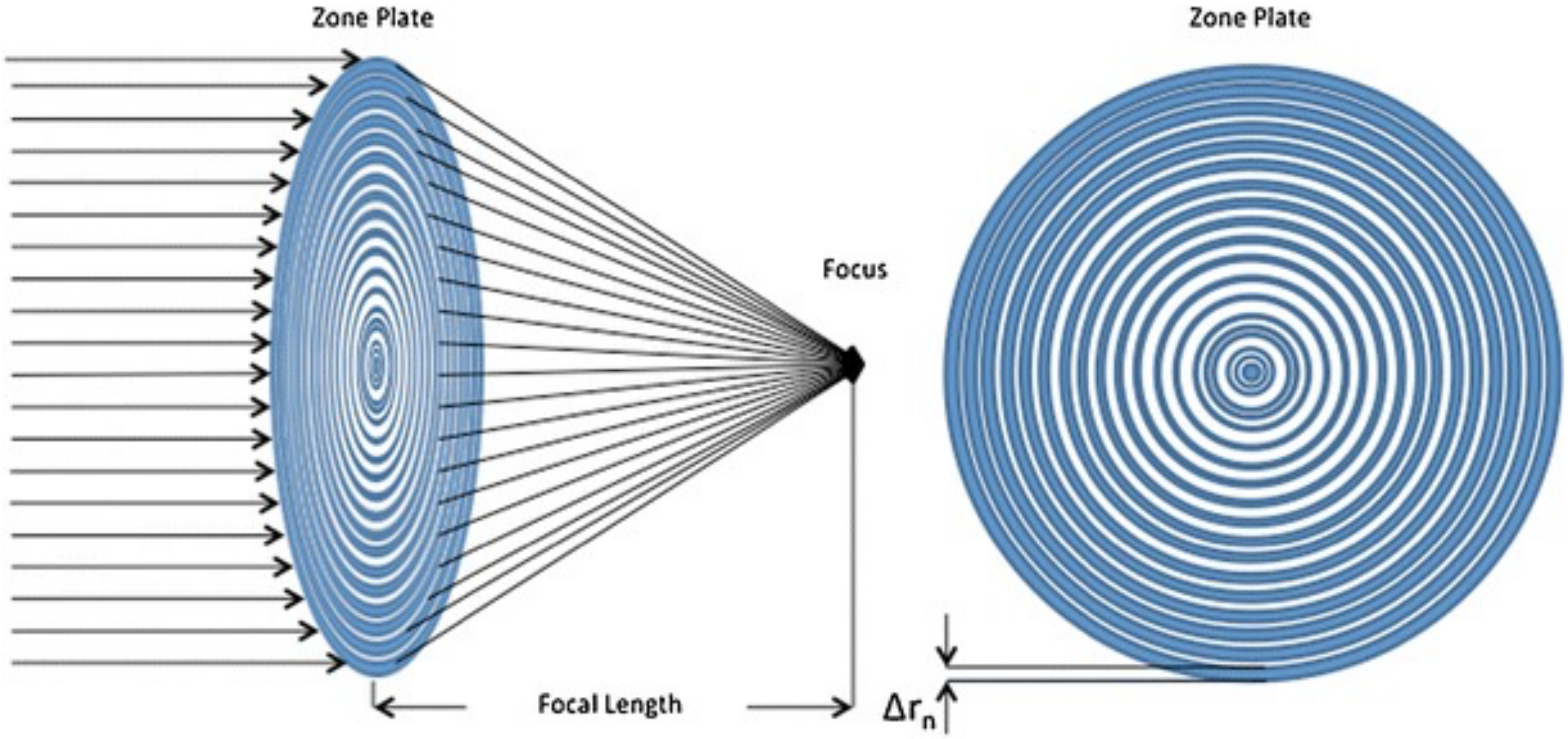
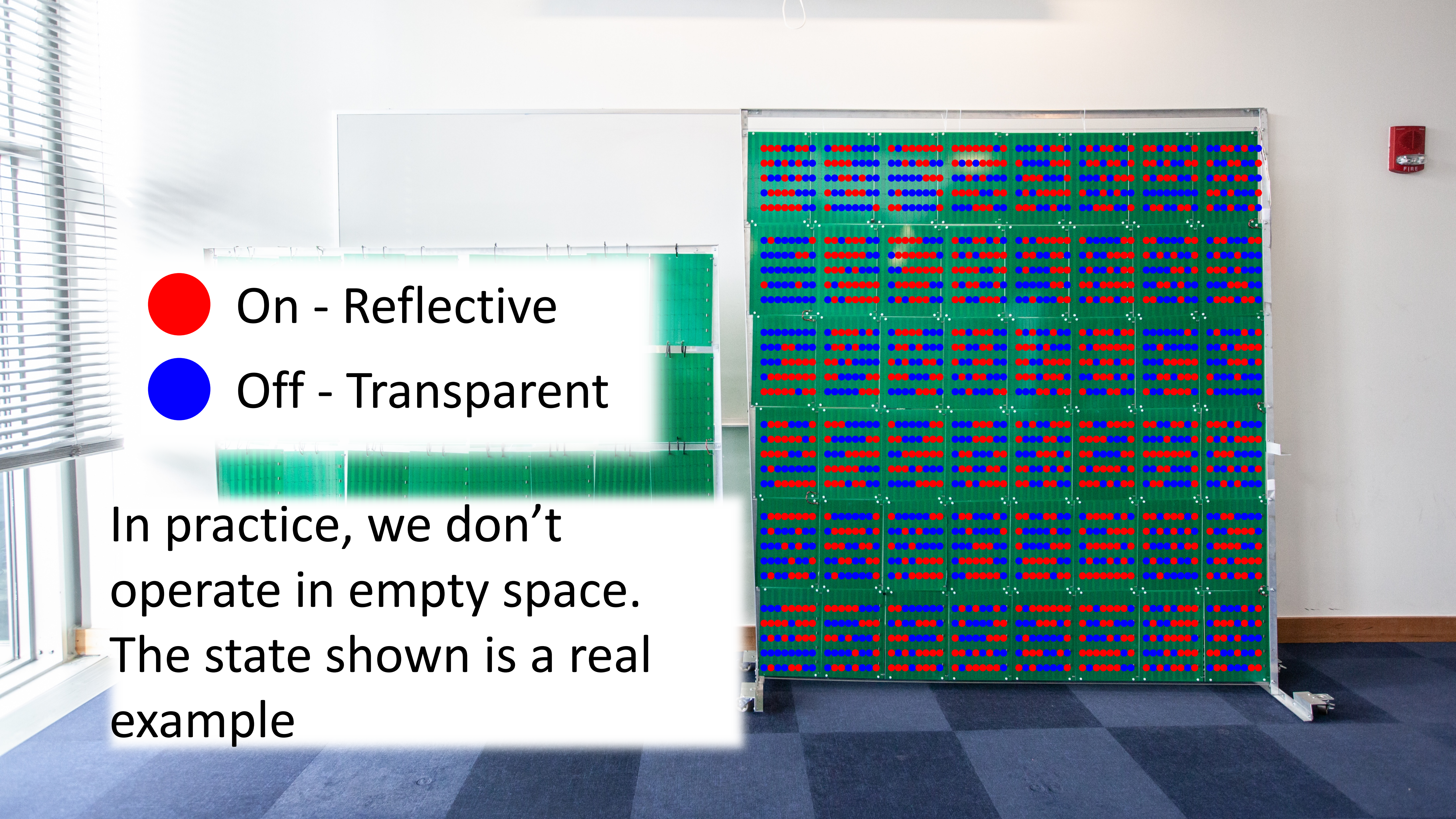
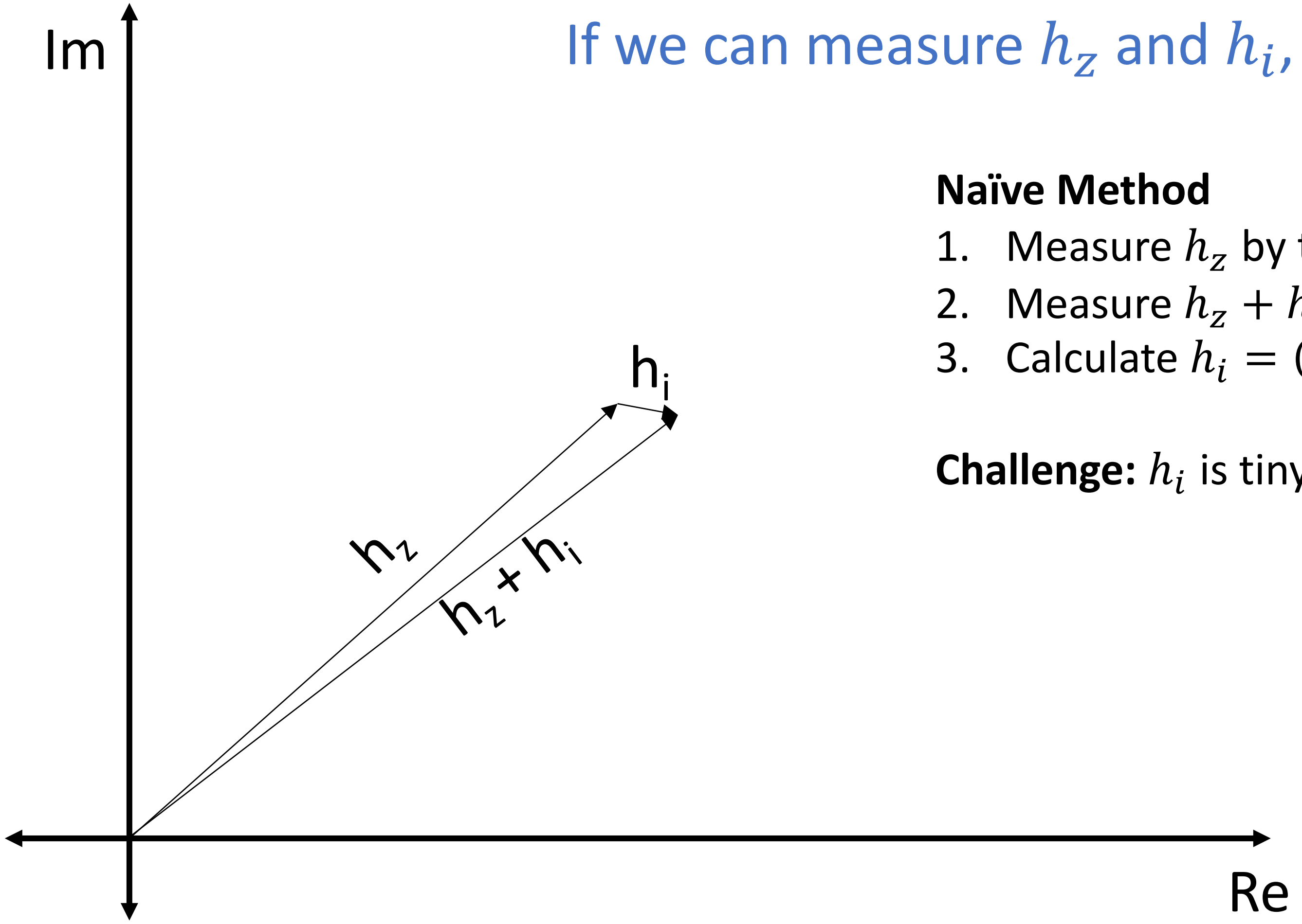



On - Reflective
Off - Transparent
In practice, we don't operate in empty space. The state shown is a real example

Strawman 1: Prior Work



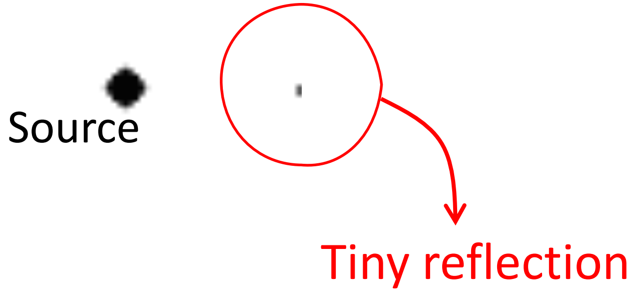
If we can measure h_z and h_i, we can find the optimum state

Naïve Method

1. Measure h_z by turning all antennas off
2. Measure $h_z + h_i$ by turning just the i^{th} antenna on
3. Calculate $h_i = (h_z + h_i) - h_z$

Challenge: h_i is tiny!

h_i are tiny and hard to measure



Prior Work

- Large body of theoretical work and some experimental work
- They do not address the problem of measuring h_i
- Hence cannot scale to larger distances and larger number of antennas
- RFocus is the first large-scale prototype to demonstrate the feasibility of such a system
- Increasing interest in the CS community

- "Optimally diverse communication channels in disordered envi-ronments with tuned randomness", P. del Hougne, M. Fink, and G. Lerosey
- "Shaping complex microwave fields in reverberating media withbinary tunable metasurfaces", N. Kaina, M. Dupré, G. Lerosey, and M. Fink
- "Increasing indoor spectrum sharing capacity using smart reflect-array", X. Tan, Z. Sun, J. M. Jornet, and D. Pados

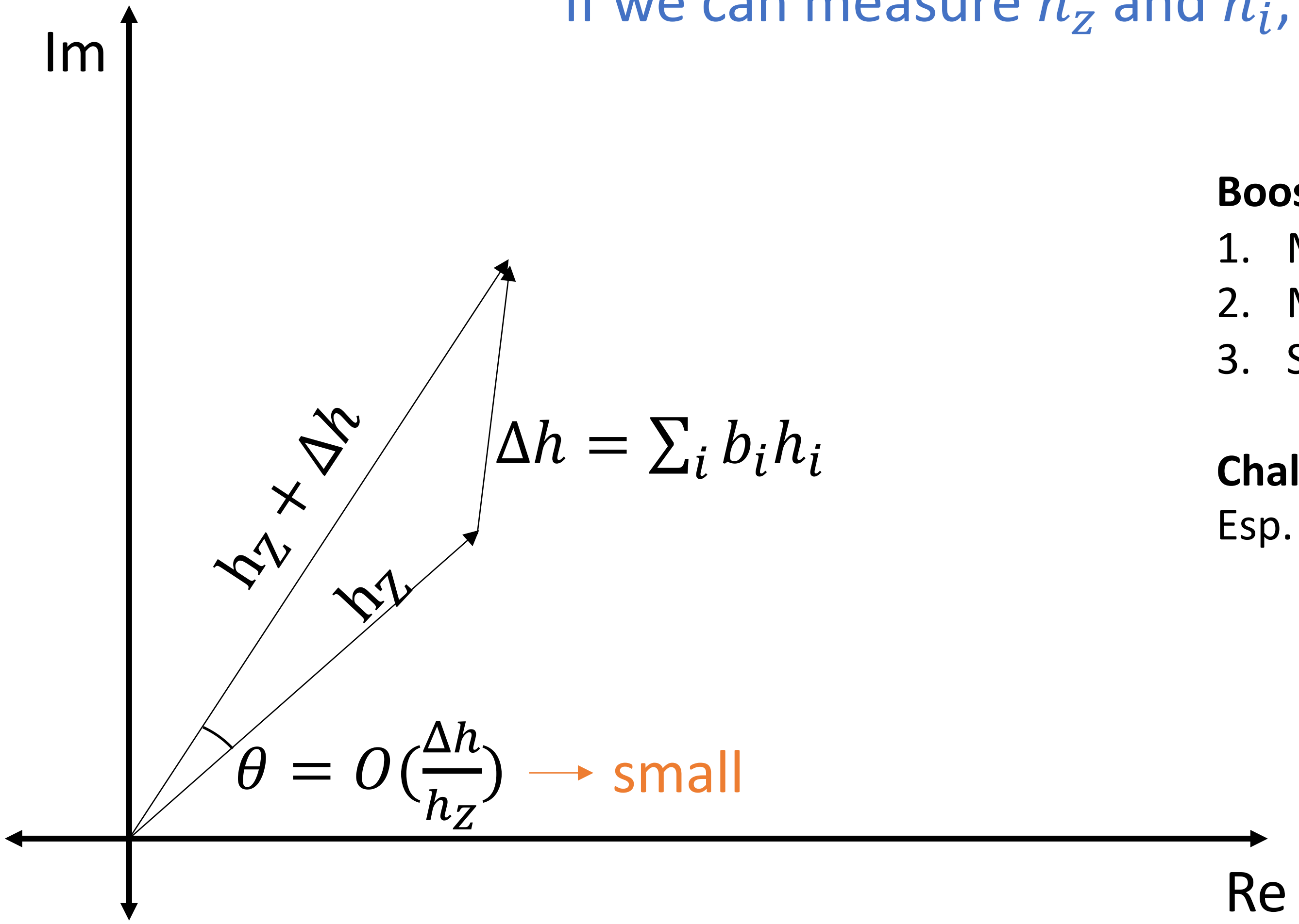
Key Ideas: to measure tiny h_i

- **Boosting:** Instead of measuring the effect of one antenna, turn on a random subset of antennas and measure the effect
  - This effect is $\mathrm{O(N)}$ times bigger (here, $\mathrm{N} = 3200\times$)

- **Signal Strength:** The effect on phase is still small, esp. due to clock jitter and CFO drift. Rely only on signal strength (RSSI) instead.

Strawman 2: Boosting

If we can measure h_z and h_i, we can find the optimum state



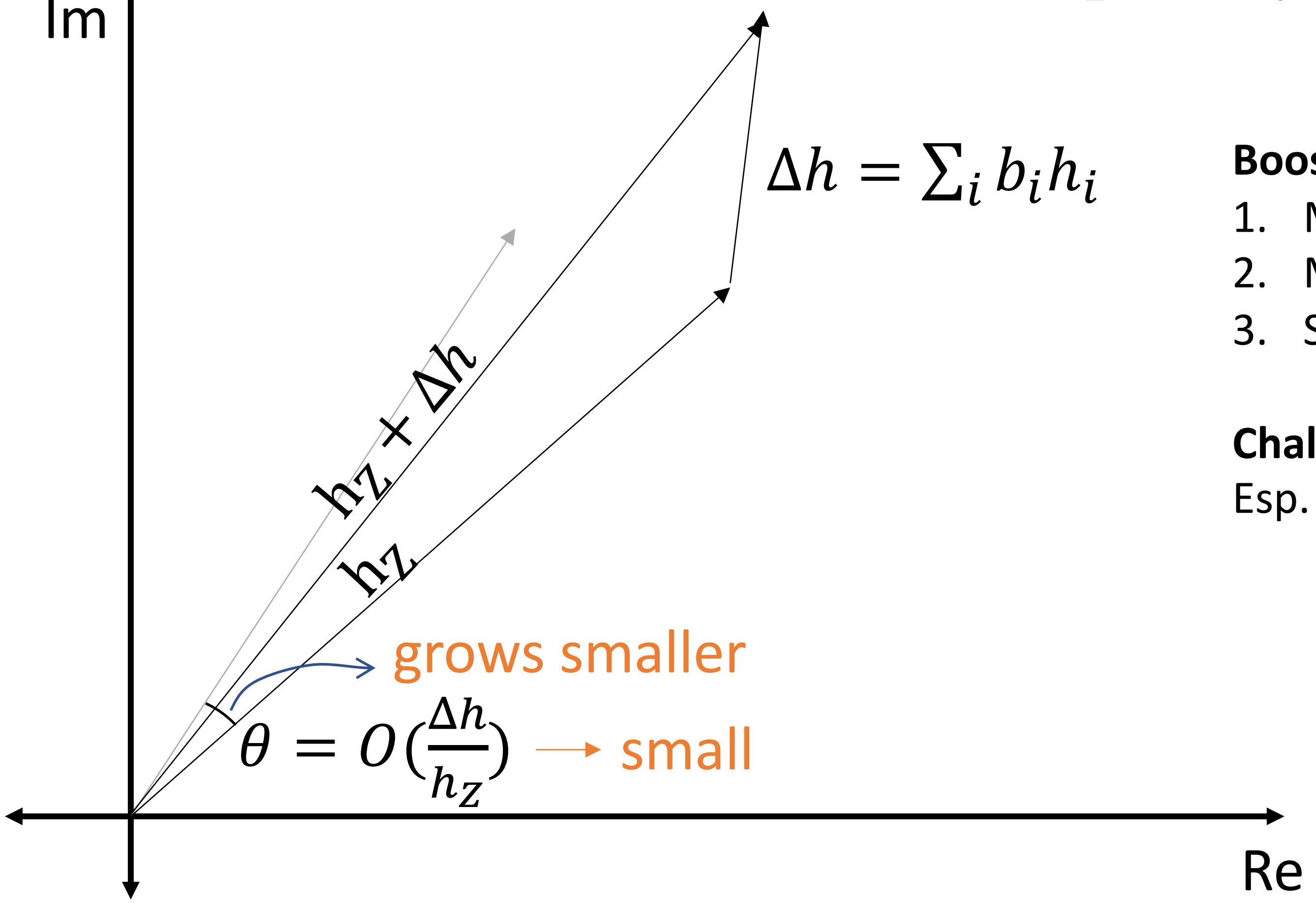
Boost the Signal:

1. Measure h_Z
2. Measure $h_z + \sum_i b_i h_i$ for many random b_i
3. Solve linear equations for h_i

Challenge: $\sum_i b_i h_i$ is still small!
Esp. phase change is small

Strawman 2: Boosting

If we can measure h_z and h_i, we can find the optimum state



Boost the Signal:

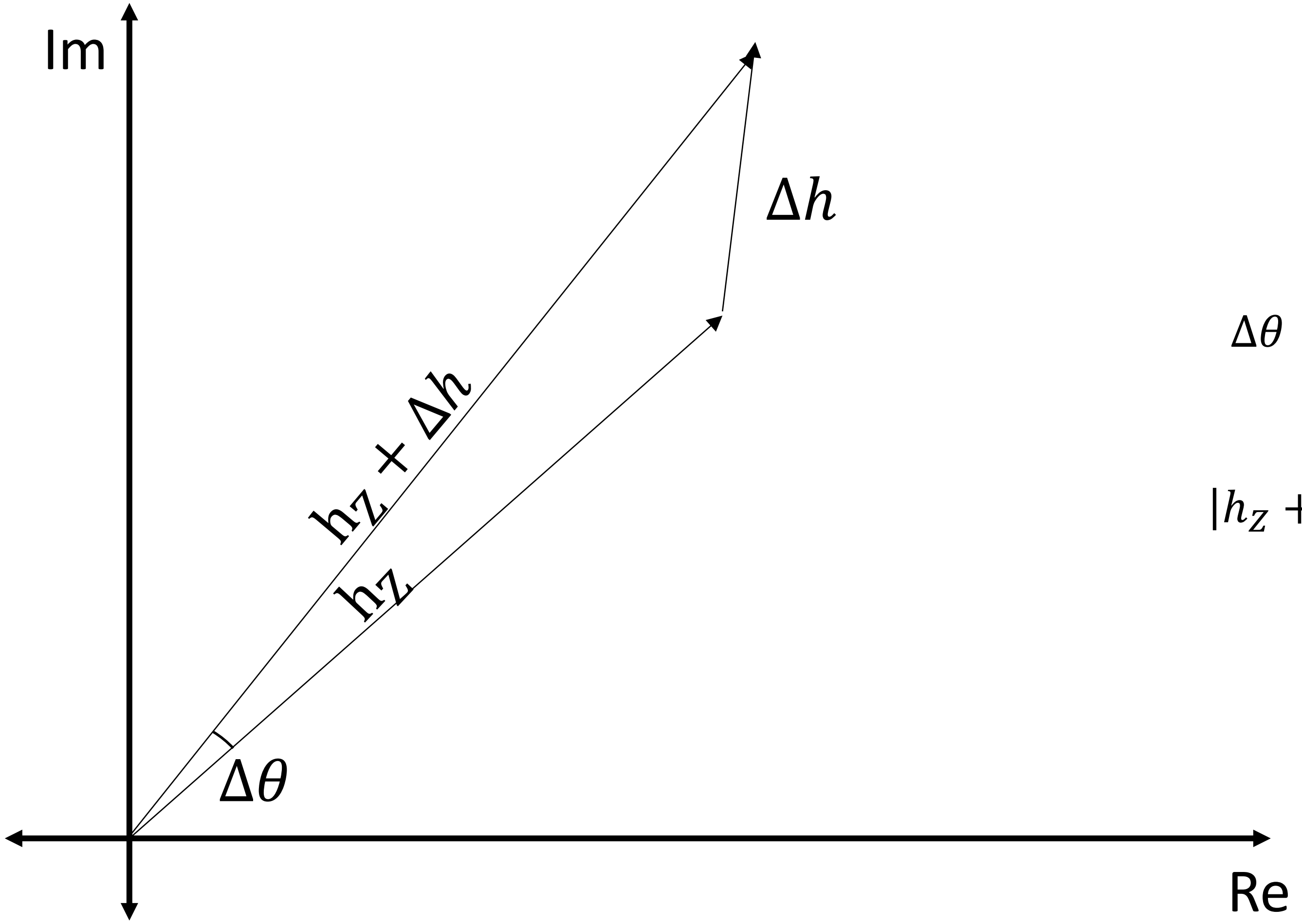
1. Measure h_Z
2. Measure $h_z + \sum_i b_i h_i$ for many random b_i
3. Solve for linear equations h_i

Challenge: $\sum_i b_i h_i$ is still small!
Esp. phase change is small

Assumptions

1. The phases of h_i are uniformly distributed random variables in $(-\pi, \pi]$
2. For uniformly random **b**, $|\sum_i b_i h_i| \ll |h_Z|$ with high probability
3. $|h_i|$ is bounded above by a constant, even as $N \to \infty$

Measuring signal strength is easier than measuring phase



When $\Delta h \ll h_Z$,

$$\Delta\theta = Arg(h_Z + \Delta h) - Arg(h_Z) \approx \Im(\frac{\Delta h}{h_Z})$$

$$|h_Z + \Delta h| - |h_z| \approx |h_z| \Re\left(\frac{\Delta h}{h_z}\right) = \frac{\Re(\Delta h\, h_Z^*)}{|h_Z|}$$

How we take measurements

Antenna ID →

1	2	3	4	signal strength Measurement
0	1	1	0	0.8
1	1	1	0	0.9
0	0	1	1	1
1	0	0	0	1.1
1	1	0	1	1.1

Strawman 3: Take the max of all rows

Antenna ID →

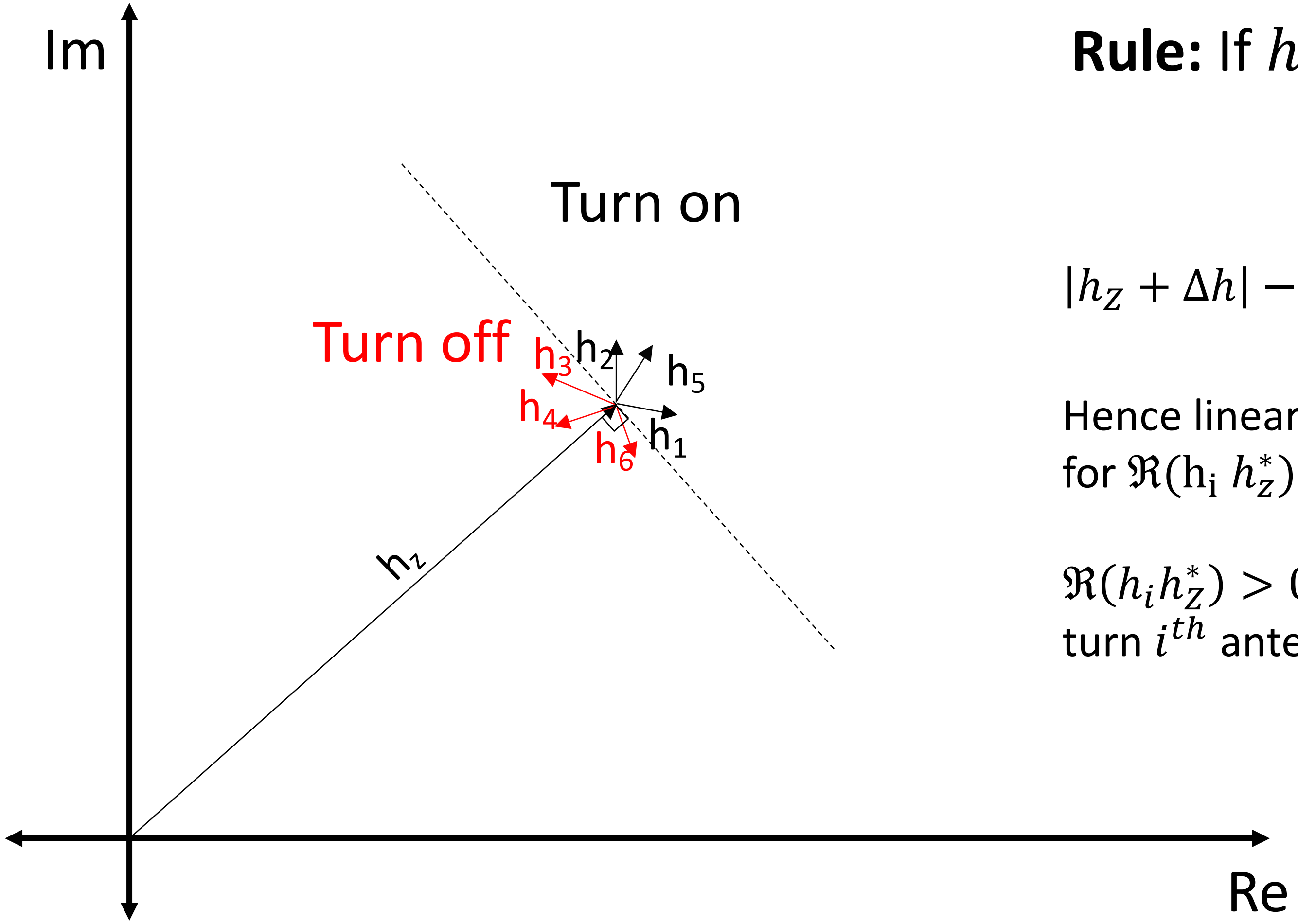
1	2	3	4	signal strength Measurement
0	1	1	0	0.8
1	1	1	0	0.9
0	0	1	1	1
1	0	0	0	1.1
1	1	0	1	1.1

Very far from optimal

Most random states have 1% the impact of the zeros state (h_Z)

The optimal state is $\sim 10\times$ bigger

Approach: Linear Regression



Rule: If h_i makes an acute angle with h_z, turn it on

$$|h_Z + \Delta h| - |h_Z| \approx |h_z| \Re\left(\frac{\Delta h}{h_z}\right) = \frac{\Re(\Delta h\ h_Z^*)}{|h_Z|}$$

Hence linear regression on $|h_z + \sum_i b_i h_i|$ will solve for $\Re(\mathrm{h_i}\ h_z^*)$, which gives us our answer

$\Re(h_i h_Z^*) > 0 \Rightarrow h_i$ makes an acute angle with $h_Z \Rightarrow$ turn i^{th} antenna on

Why not linear regression?

- Sensitive to outliers because it minimizes RMS error. Our approach looks at the median
  - This was a problem with an earlier version of RFocus
- Computationally expensive
- Our approach can fix the state of an antenna as soon as we are 95% sure about its value

Why not linear regression?

- Our approach can fix the state of an antenna as soon as we are 95% sure about its value
  - If an antenna is faulty, it doesn’t affect the others
  - Maybe only a small fraction of antennas are close enough to have an effect. Here, we can set those as soon as we are sure
  - The optimization algorithm is embarrassingly parallel for different antennas

Our Approach: Majority Voting

Antenna ID →

1	2	3	4	Signal strength Measurement
0	1	1	0	0.8
1	1	1	0	0.9
0	0	1	1	1
1	0	0	0	1.1
1	1	0	1	1.1

→ Median

Our Approach: Majority Voting

Antenna ID →

1	2	3	4	Signal strength Measurement
0	1	1	0	0.8
1	1	1	0	0.9
0	0	1	1	1
1	0	0	0	1.1
1	1	0	1	1.1

This is bad,
flip what we were doing

→ Median

This is good,
Keep doing the same things

Our Approach: Majority Voting

Antenna ID →	1	2	3	4	Signal strength Measurement
	~~0~~1	~~1~~0	~~1~~0	~~0~~1	0.8
	~~1~~0	~~1~~0	~~1~~0	~~0~~1	0.9
	0	0	1	1	1
	1	0	0	0	1.1
	1	1	0	1	1.1
Majority Vote	1				

This is bad,
flip what we were doing

→ Median

This is good,
Keep doing the same things

Our Approach: Majority Voting

Antenna ID →

1	2	3	4	Signal strength Measurement
~~0~~1	~~1~~0	~~1~~0	~~0~~1	0.8
~~1~~0	~~1~~0	~~1~~0	~~0~~1	0.9
0	0	1	1	1
1	0	0	0	1.1
1	1	0	1	1.1

This is bad,
flip what we were doing

→ Median

This is good,
Keep doing the same things

Majority Vote

1	0		

Our Approach: Majority Voting

Antenna ID →	1	2	3	4	Signal strength Measurement
	~~0~~1	~~1~~0	~~1~~0	~~0~~1	0.8
	~~1~~0	~~1~~0	~~1~~0	~~0~~1	0.9
	0	0	1	1	1
	1	0	0	0	1.1
	1	1	0	1	1.1

This is bad,
flip what we were doing

→ Median

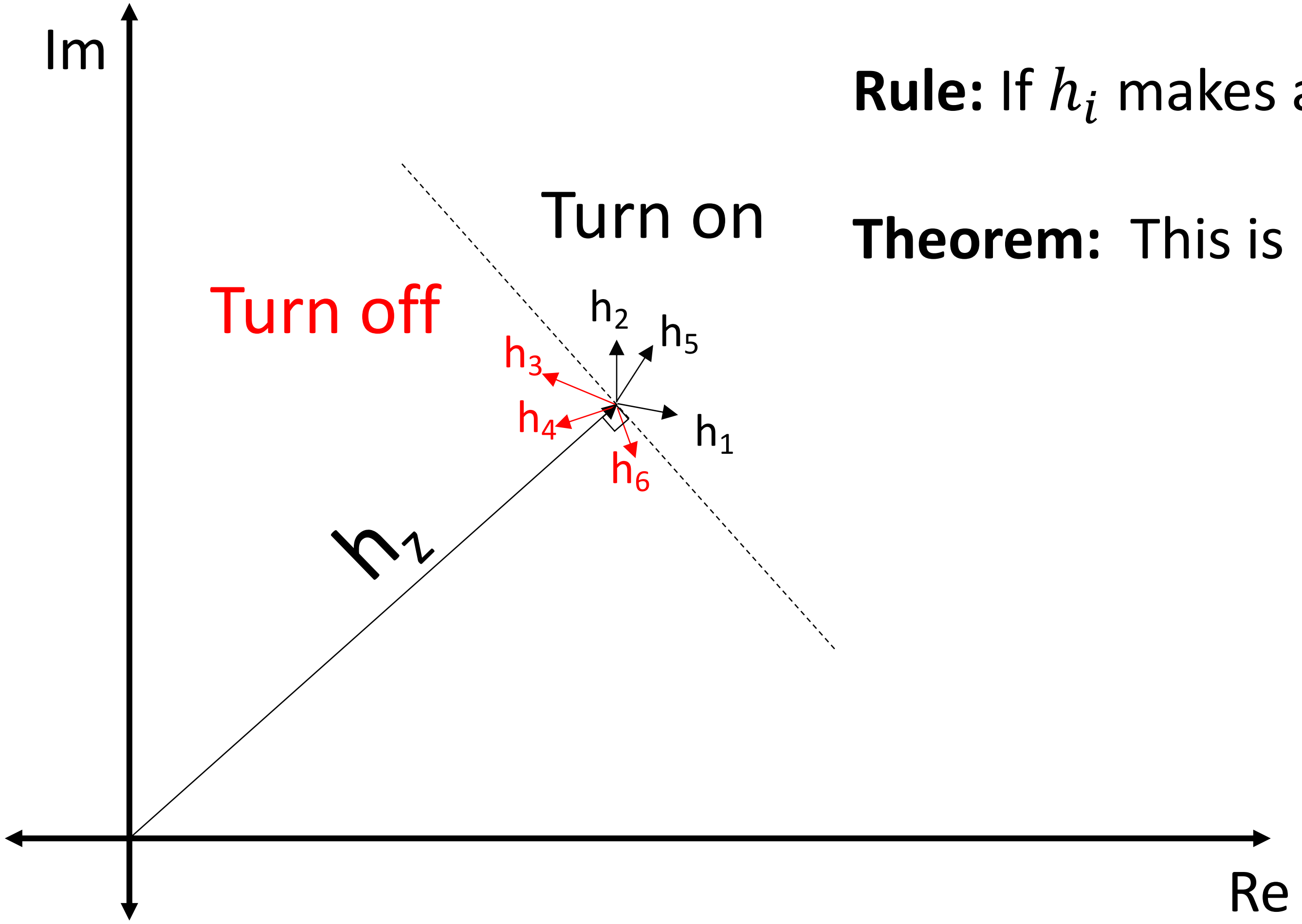
This is good,
Keep doing the same things

Majority Vote	1	0	0	1

→ Optimized State

Theorem 1: Let assumptions 1, 2 and 3 hold. Then as $N \rightarrow \infty$ and $K \rightarrow \infty$, majority voting finds a near-optimal solution. Here K is the number measurements.

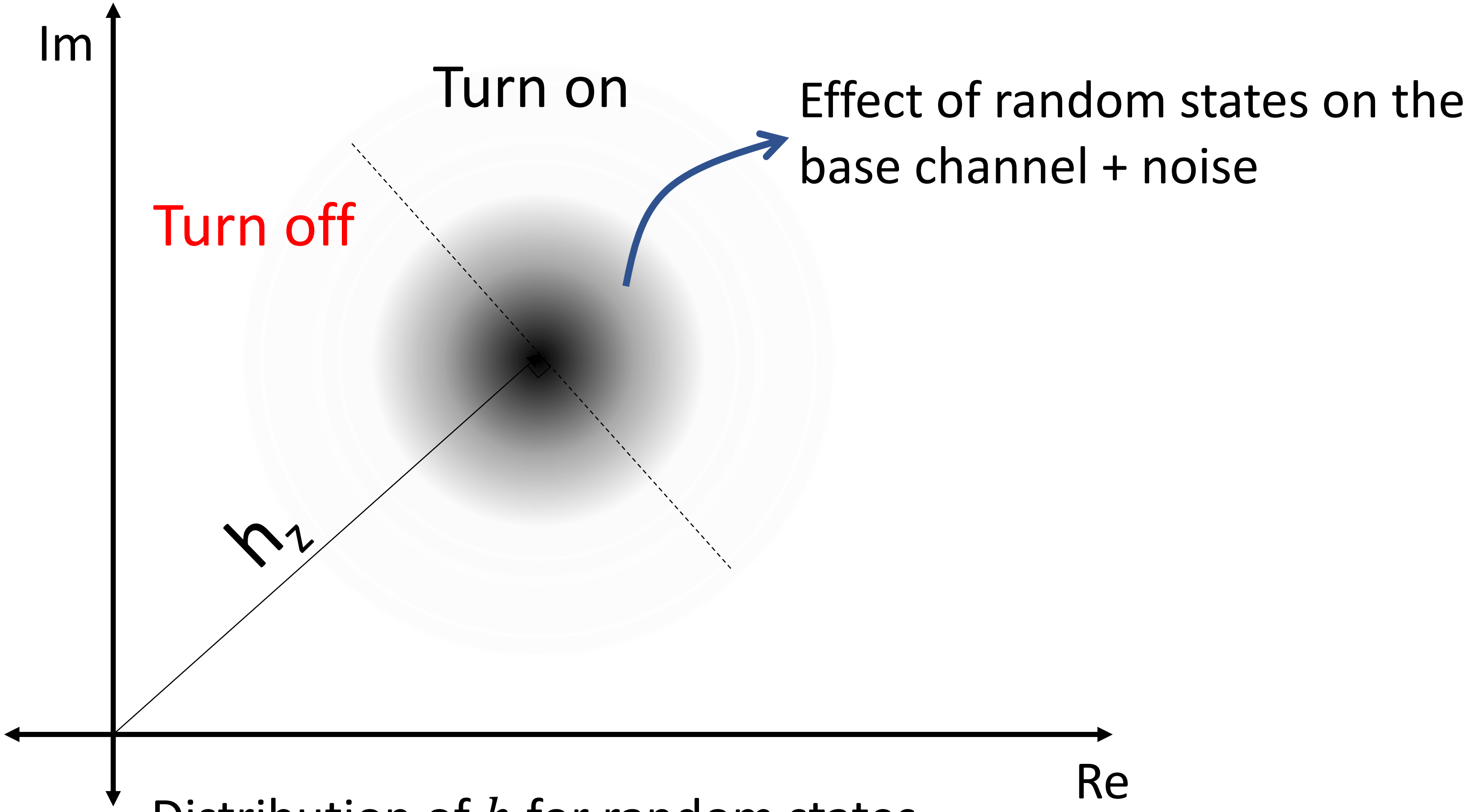
Why Majority Voting is Optimal



Rule: If h_i makes an acute angle with h_z, turn it on

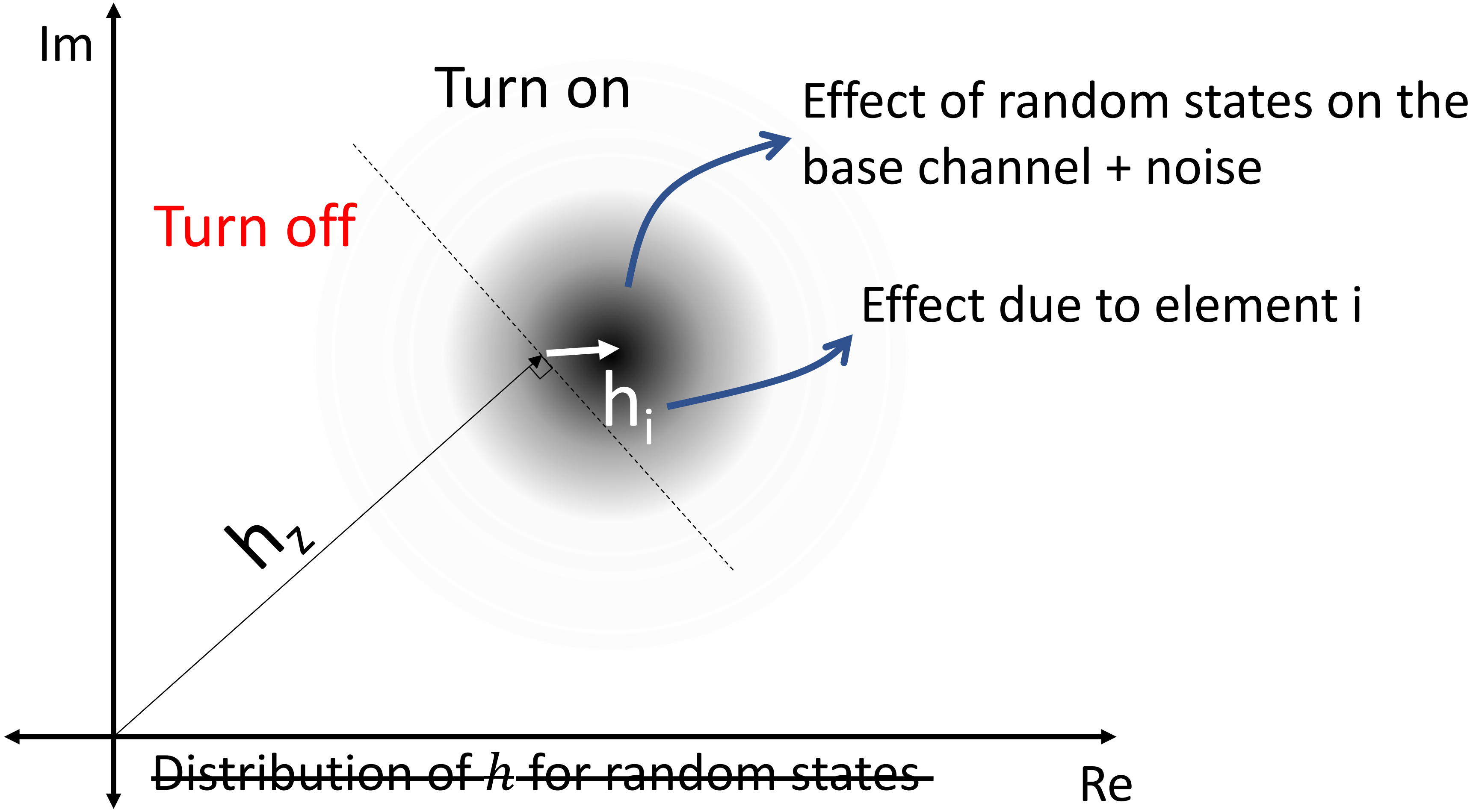
Theorem: This is near optimal

Why Majority Voting is Optimal



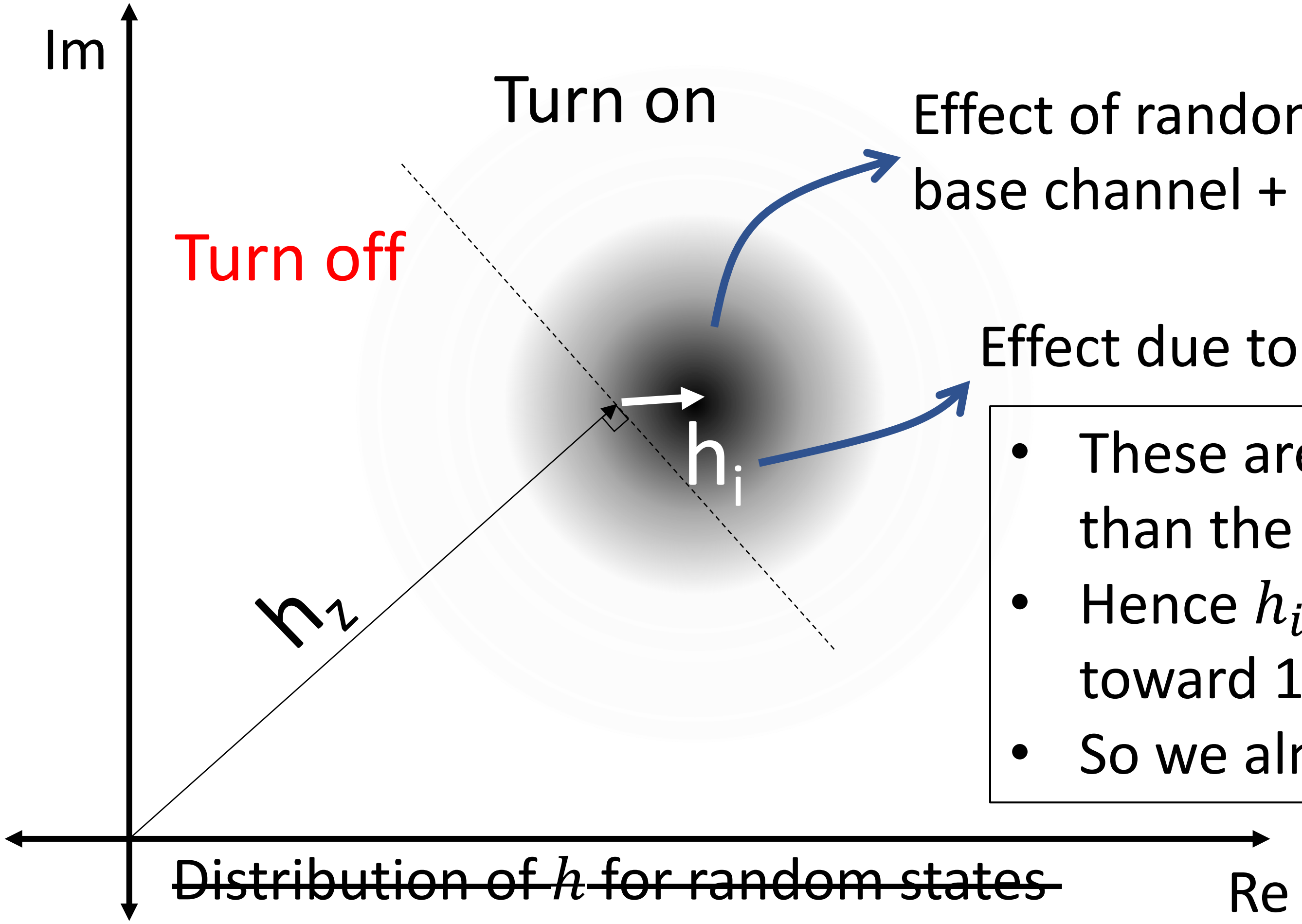
Distribution of h for random states

Why Majority Voting is Optimal



~~Distribution of h for random states~~
Distribution of h for those random states where i^{th} element is on

Why Majority Voting is Optimal



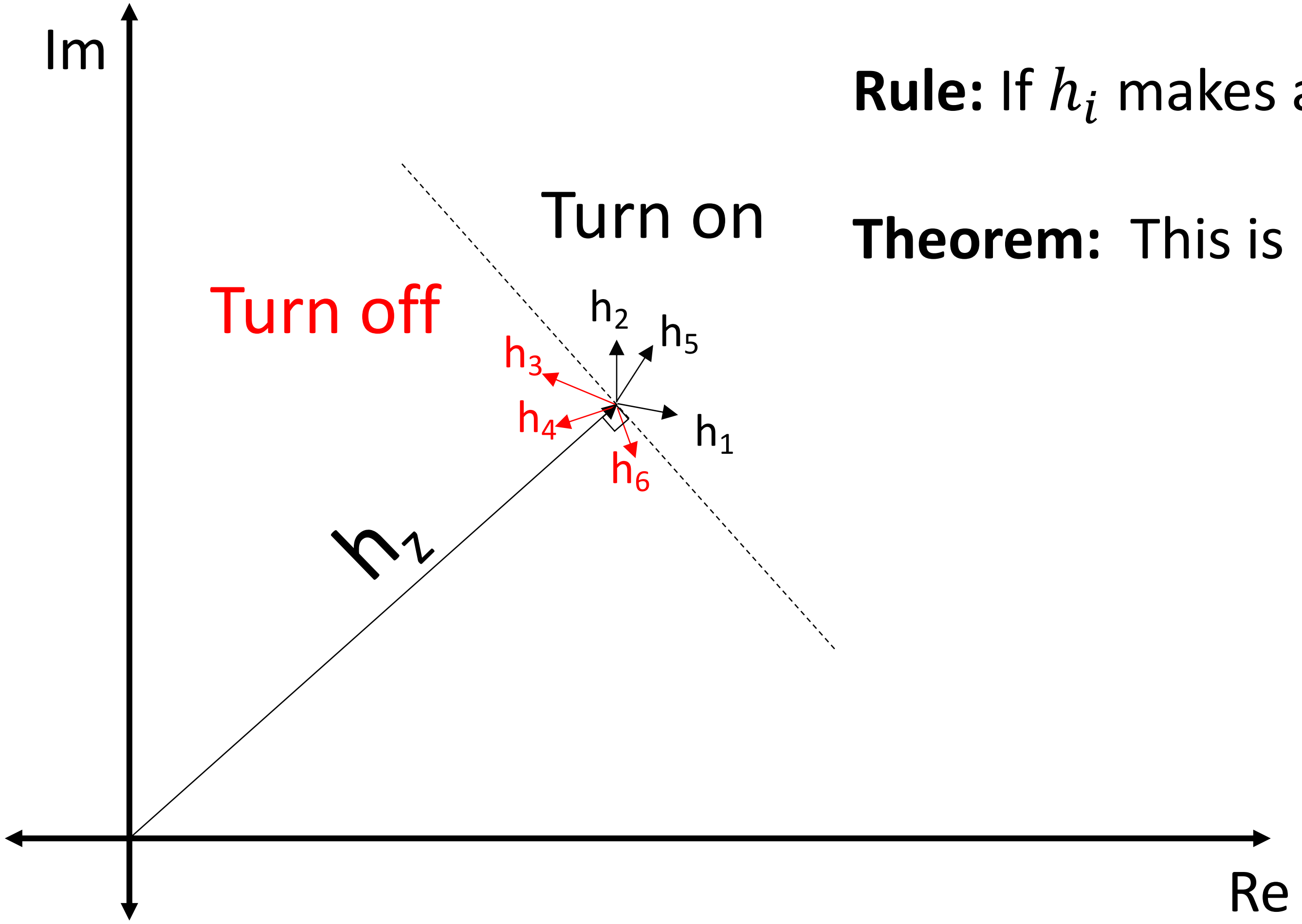
Effect of random states on the base channel + noise

Effect due to element i

- These are slightly more likely to be **greater** than the median
- Hence h_i is slightly more likely to receive votes toward 1
- So we almost certainly turn it h_i **on**

Distribution of h for those random states where i^{th} element is on

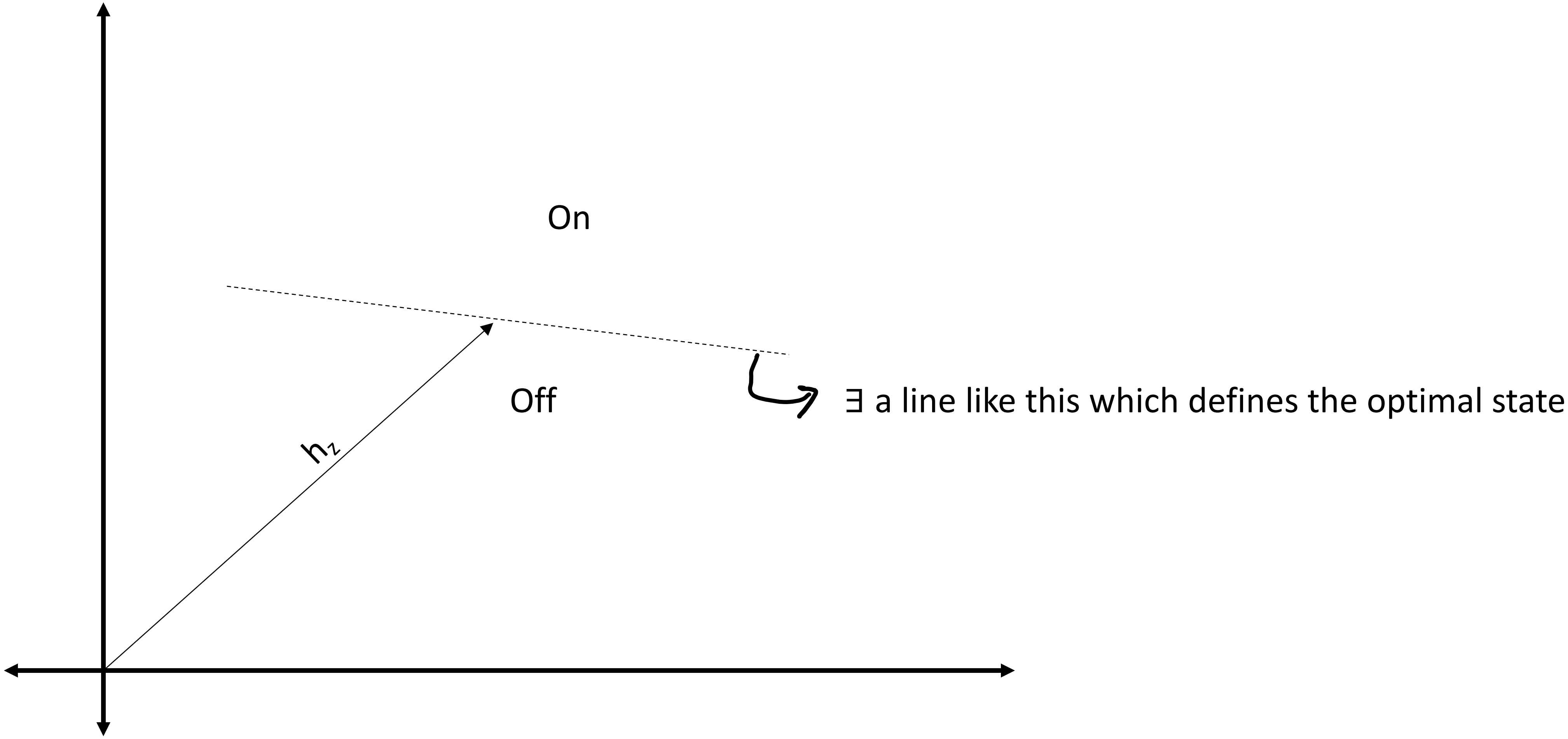
Why Majority Voting is Optimal



Rule: If h_i makes an acute angle with h_z, turn it on

Theorem: This is near optimal

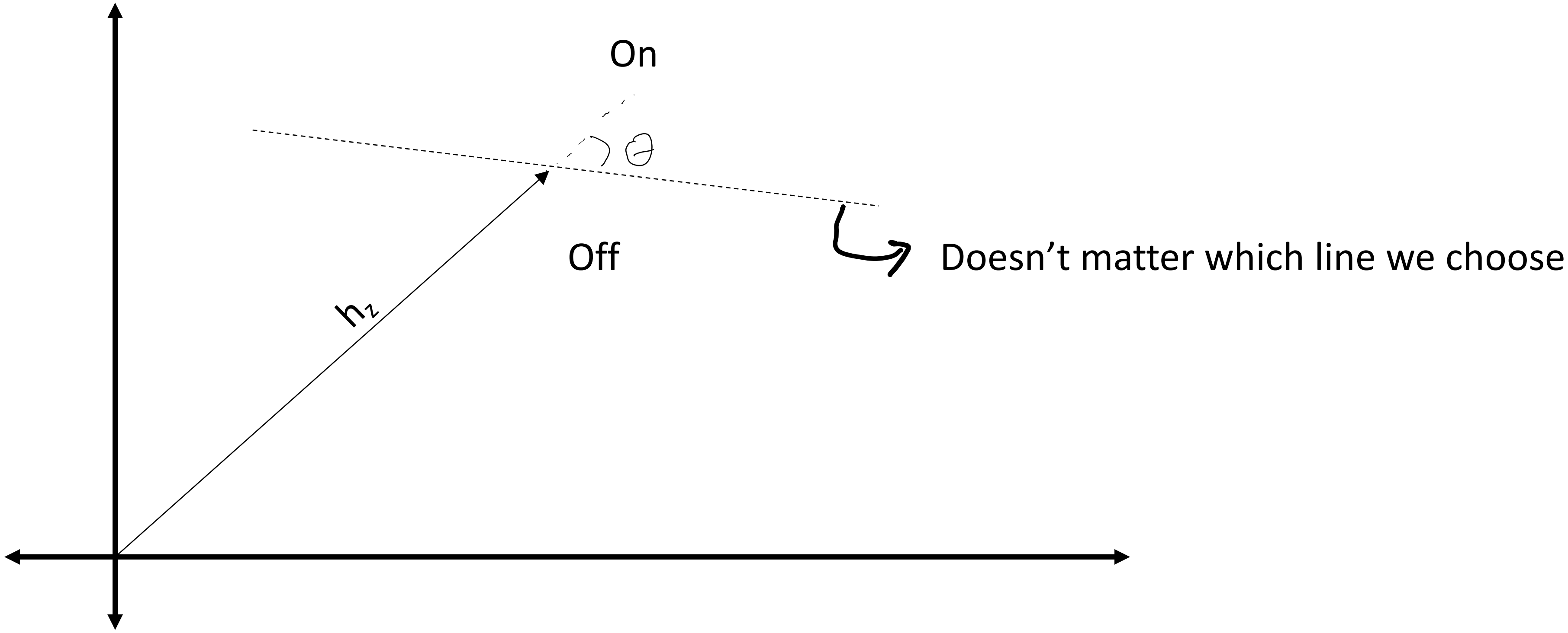
Lemma 1: Under assumptions 2 and 3, let $\boldsymbol{b}_{OPT}$ be an optimal state assignment. Then $b_{OPT,i} = 1$ if and only if $\Re(h_i \cdot H(\boldsymbol{b}_{OPT})^*) > 0$, where $H(\boldsymbol{b}) = h_Z + \boldsymbol{h} \cdot \boldsymbol{b}$.



Lemma 1: Under assumptions 2 and 3, let $\boldsymbol{b}_{OPT}$ be an optimal state assignment. Then $b_{OPT,i} = 1$ if and only if $\Re(h_i \cdot H(\boldsymbol{b}_{OPT})^*) > 0$, where $H(\boldsymbol{b}) = h_Z + \boldsymbol{h} \cdot \boldsymbol{b}$.

Lemma 2: Let $\boldsymbol{b}_{OPT}$ be the optimal assignment that maximizes $|h_Z + \boldsymbol{h} \cdot \boldsymbol{b}|$ and $\mathbf{b}_\perp$ be such that the i^{th} component $\boldsymbol{b}_{\perp,i} = 1$ if and only if $\Re(h_i \cdot h_Z^*) > 0$. As $N \to \infty$, if assumptions 1 and 3 hold, then $\frac{|H(\boldsymbol{b}_{OPT})|}{|H(\boldsymbol{b}_\perp)|} < 1 + \epsilon \ \forall \epsilon > 0$, with high probability.

Proof Intuition: $\max_\theta |\boldsymbol{b}_\theta \cdot \boldsymbol{h}| \approx \min_\theta |\boldsymbol{b}_\theta \cdot \boldsymbol{h}|$



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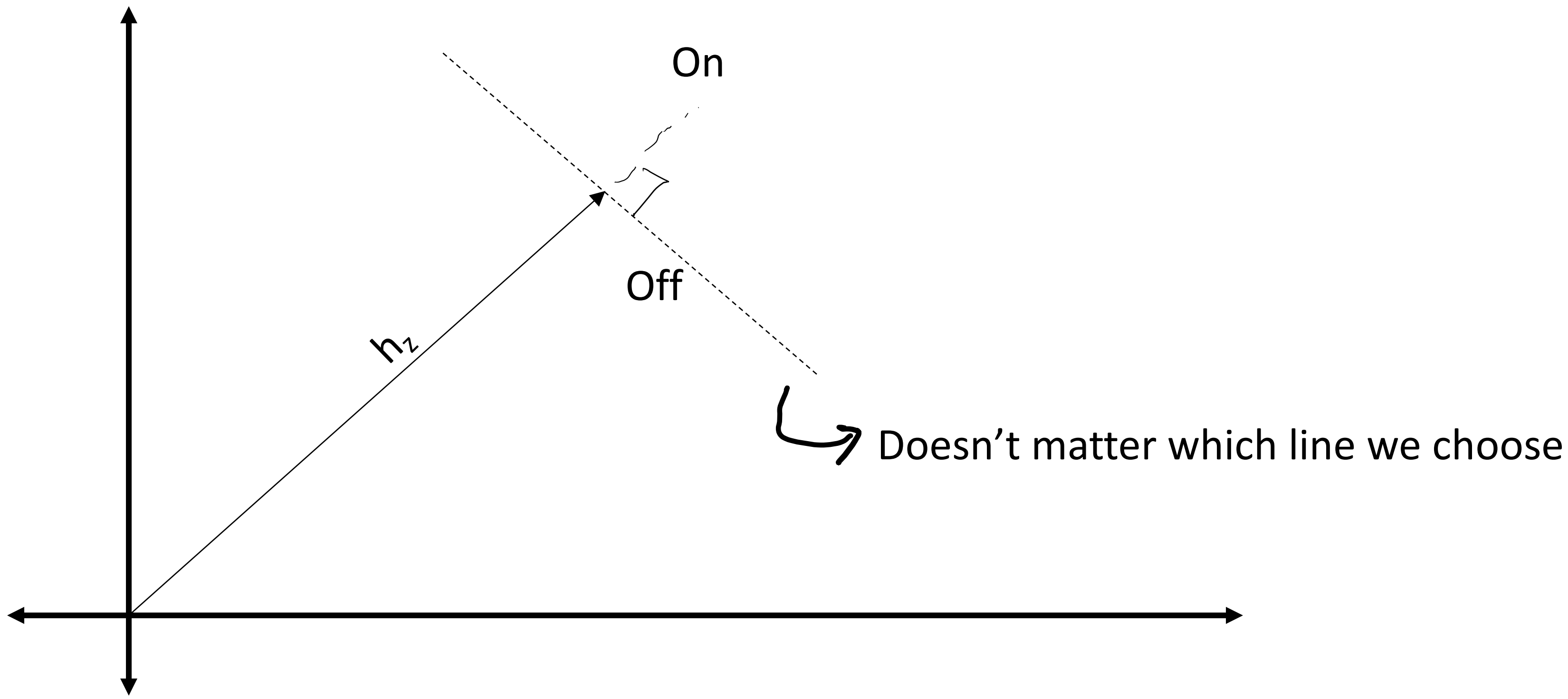
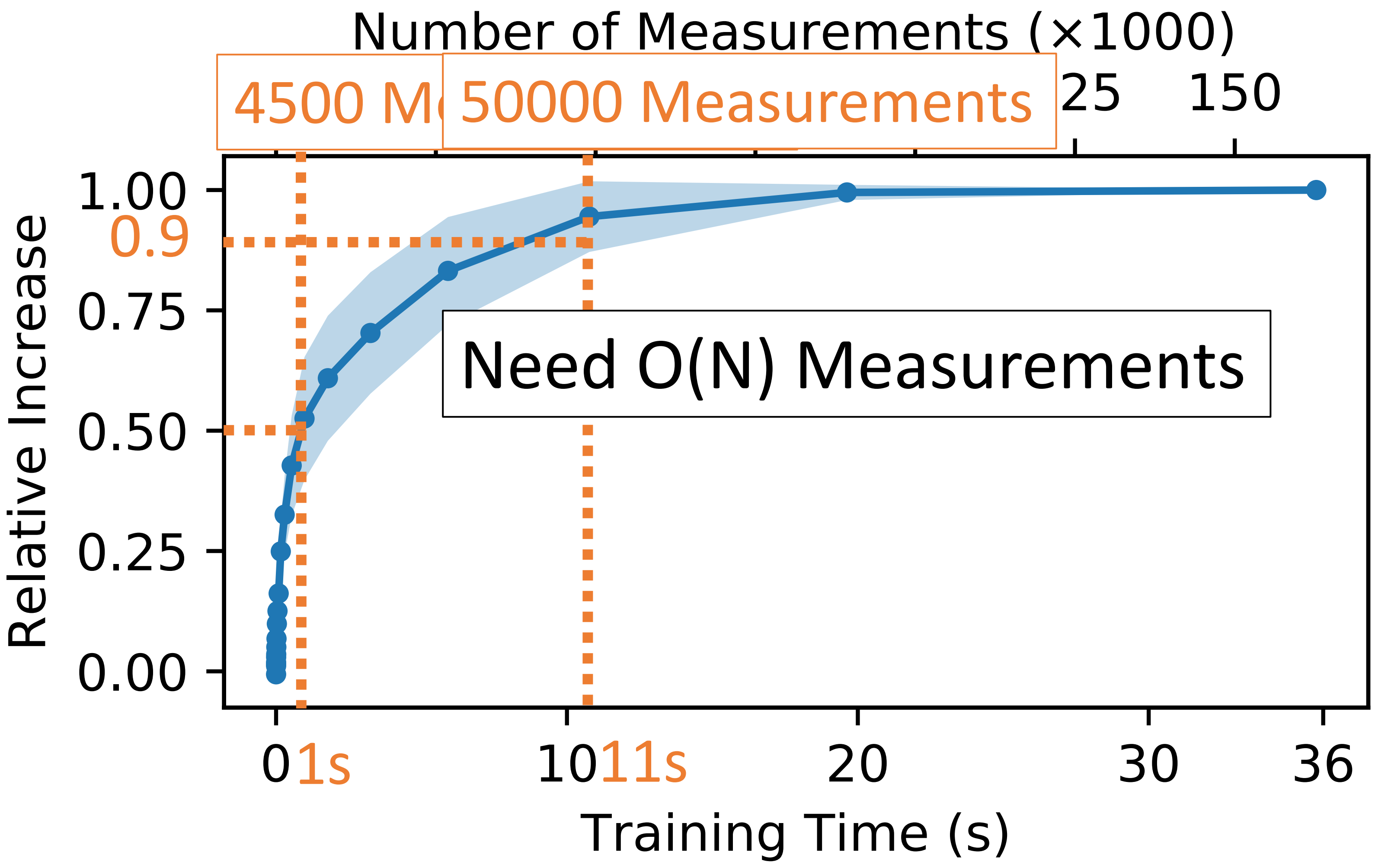
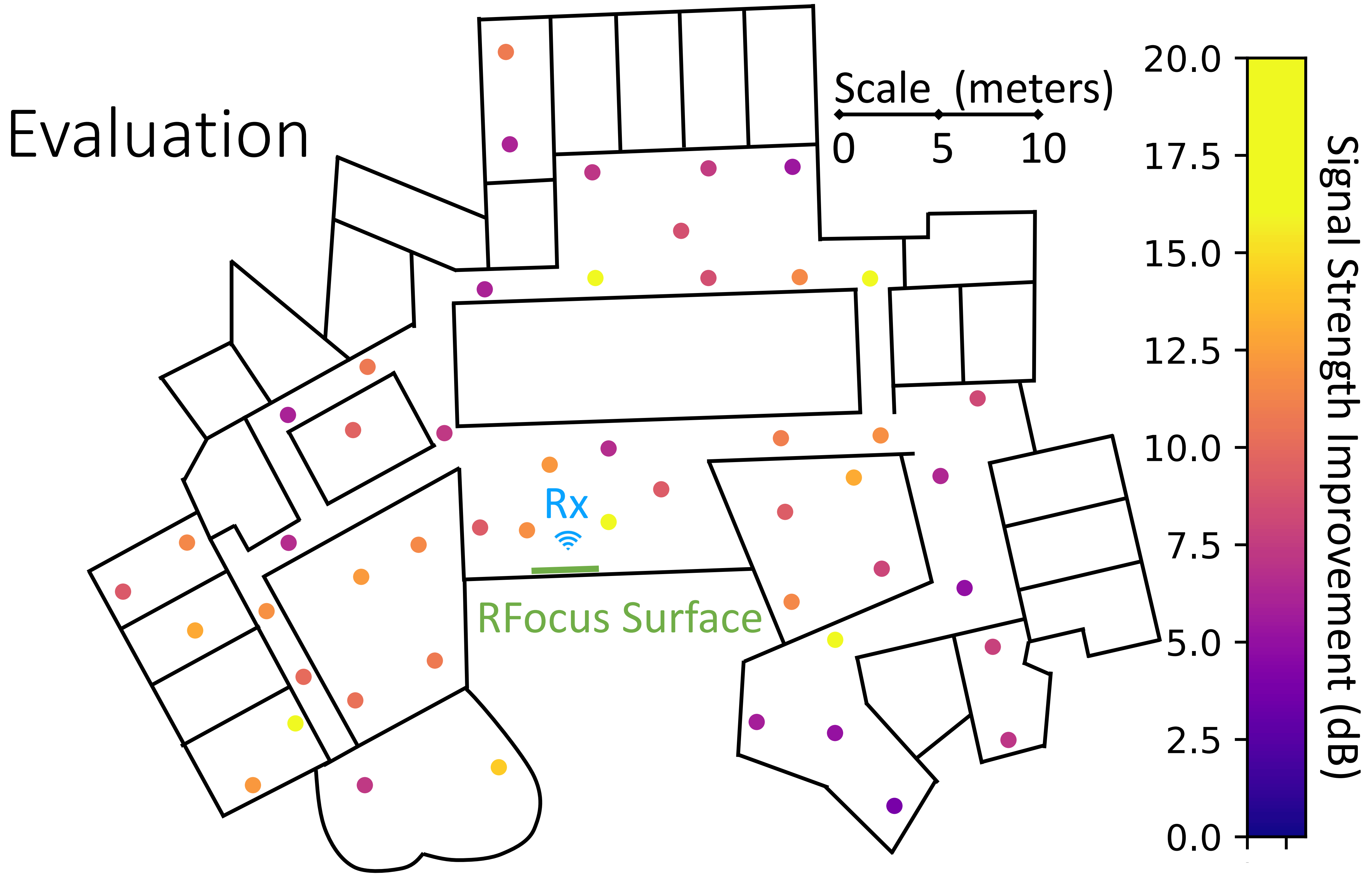


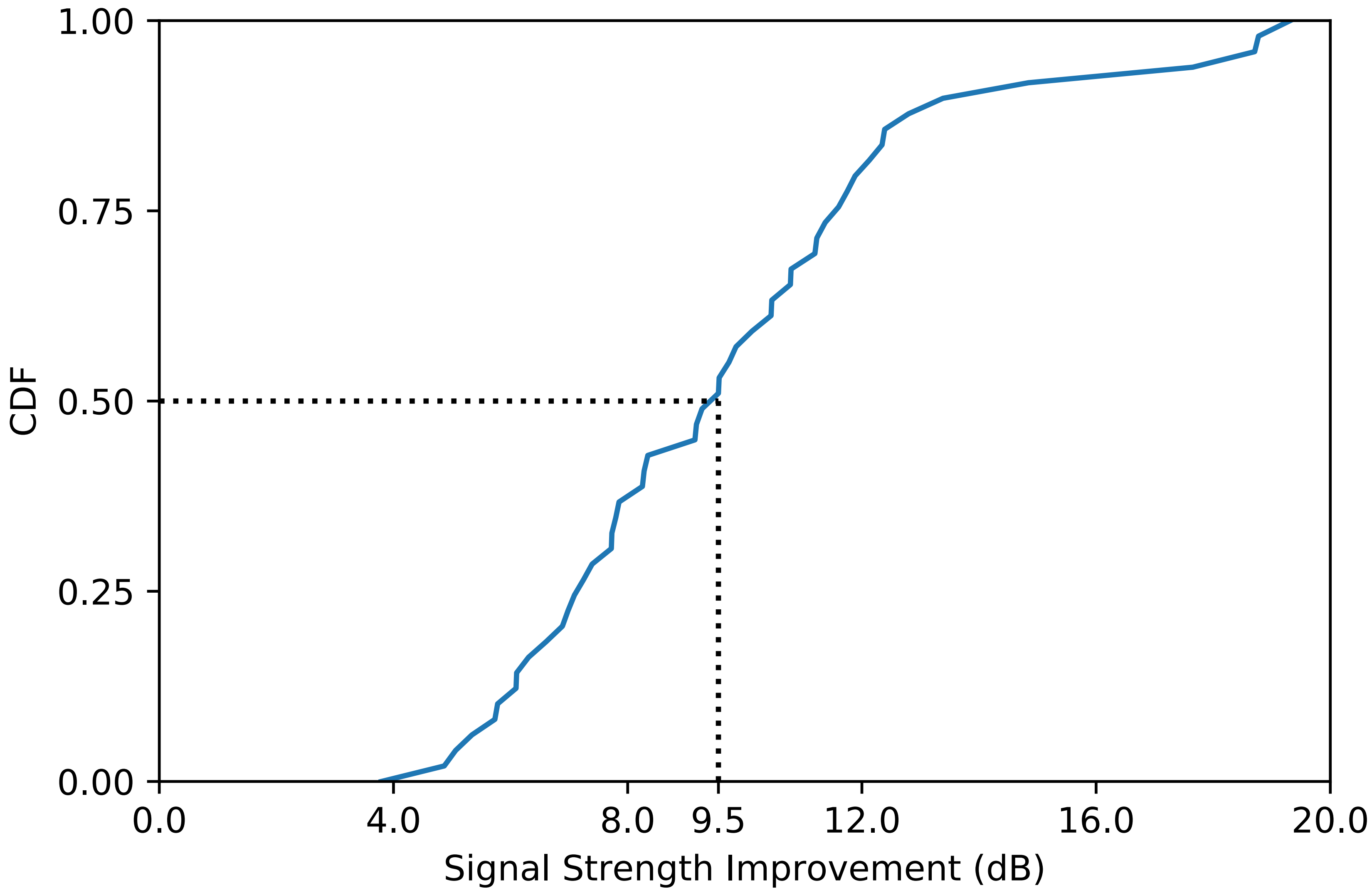
How long does it take to train?





Evaluation
Scale (meters)
0
5
10
Rx
RFocus Surface
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Signal Strength Improvement (dB)

Evaluation

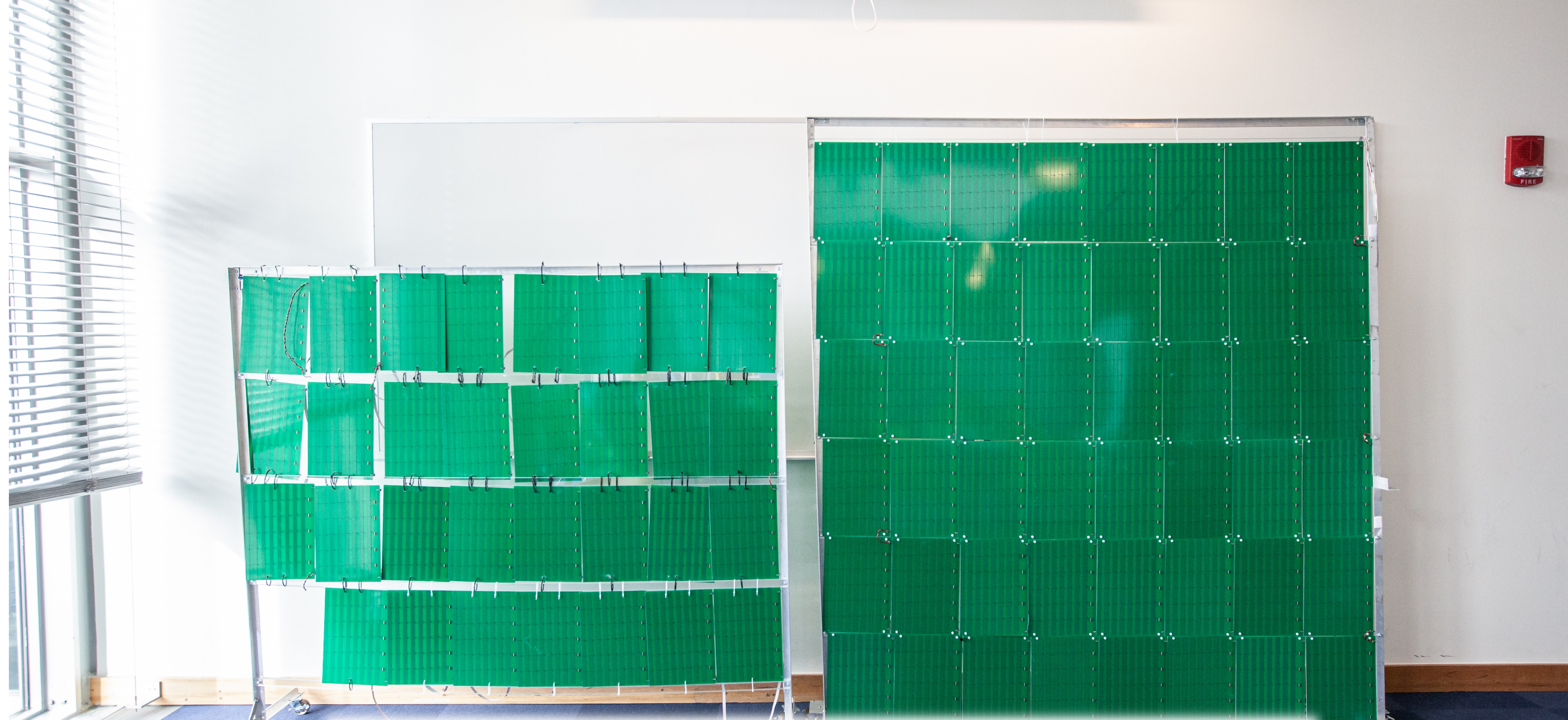


1.00
0.75
0.50
0.25
0.00
CDF
0.0
4.0
8.0
9.5
12.0
16.0
20.0
Signal Strength Improvement (dB)

Contributions

- Design of the antenna surface
- Near-optimal optimization algorithm that improves signal strength by $\approx 10\times$
  - **Challenge:** Quantities we need to measure, h_i, are $\sim$1 million times smaller than the channel

This is just the beginning!



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