IEEE WCNC' 21 Tutorial

MetaEverything: Intelligent MetaMaterial aided Sensing and Communications

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Slides available at:

http://wireless.egr.uh.edu/research.htm

Objectives

- To introduce RIS basics and potential RIS applications
  - Communication/Internet of Things
- To learn related mathematical tools to integrate RIS into future networks
  - Optimization and machine learning
- To understand how to optimize RIS aided networks
  - Communication: beamforming and deployment
  - Sensing: actively design multiple paths
  - Localization: enlarge differences

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Moving Towards 6G: Emerging Use Cases

VR/AR

AR for surgery

VR for education

Internet-of-Things

Auto-manufacturing

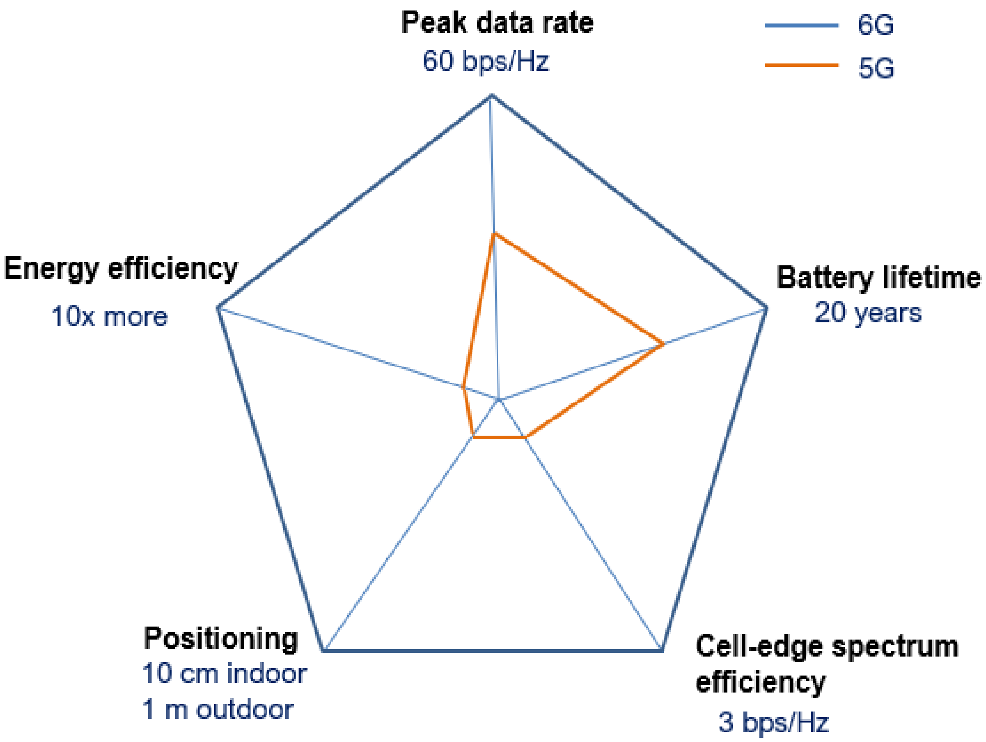
E-health

Intelligence

Smart home

Environment sensing

General 6G KPI Targets



Data source: 6G White Paper, University of Oulu

Higher data rates

Lower power consumption

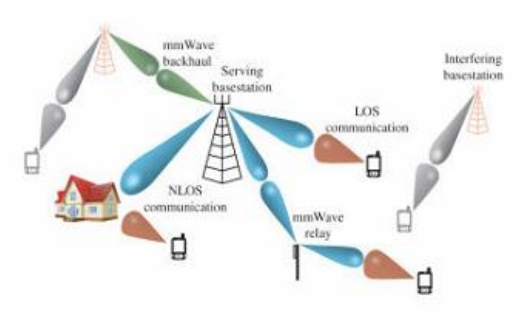
Larger Coverage

Smarter devices

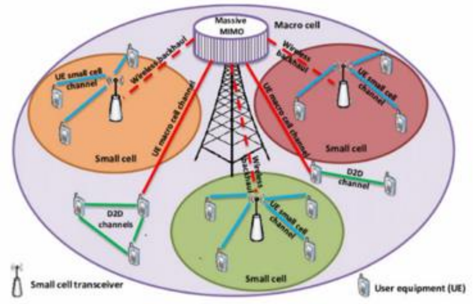
6G Challenges: Cost Efficiency

1. Conflict between low hardware cost and high data rate

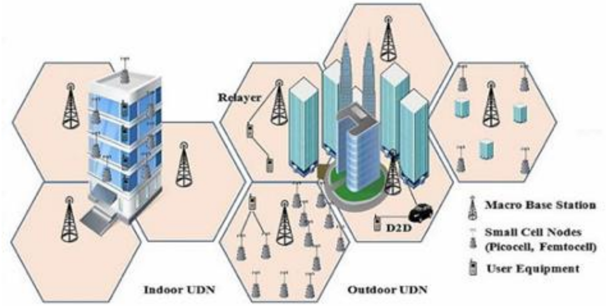
- High spatial resolution at a cost of expensive hardware
  - High-frequency communication: dedicated RF chains lead to an rapidly increasing cost as the number of users grows
  - Massive-MIMO: a huge number of antennas each with a phase shifter imposes significant cost in network deployment.
  - UD-Networking: a dense topology requires extremely high cost of deployment and coordination



High-Frequency Communications



Massive MIMO

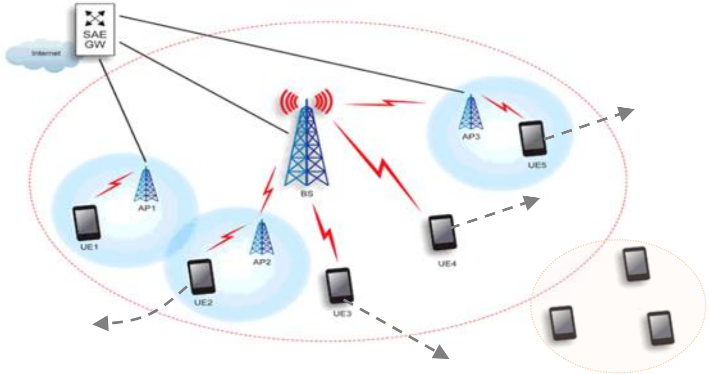


Ultra-Dense Networking

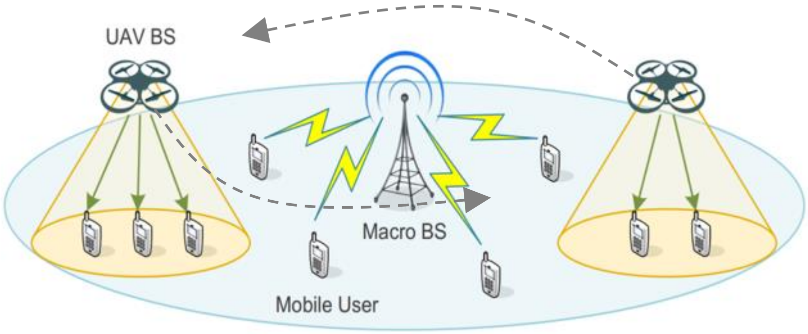
6G Challenges: Energy Efficiency

2. Conflict between flexible network deployment and low power consumption

- Fixed access points
  - No guarantee to adapt to dynamic user traffic
- Moving access points
  - Involve high energy consumption (e.g., propulsion energy and transmission energy consumption)



Fixed access points

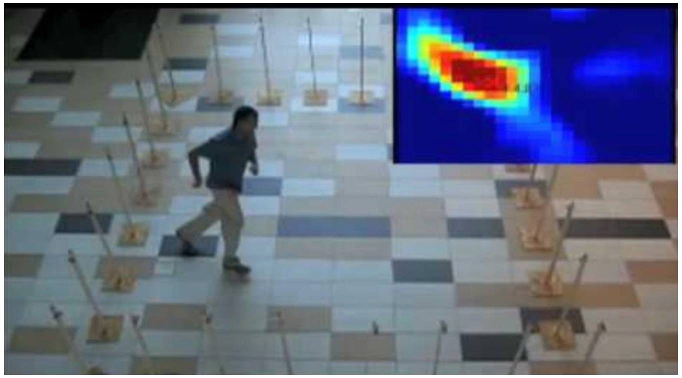


Moving access points

6G Challenges: Sensing Efficiency

3. Conflict between simplicity&comfort and high sensing accuracy

- WiFi based RF Sensing
  - Requires the cooperation of multiple WiFi access points to achieve high sensing accuracy
- mmWave Radar
  - High hardware cost makes it hard for mass deployment



WiFi based RF Sensing

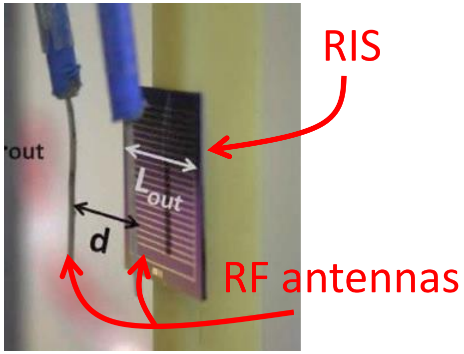
mmWave Radar

Solutions: Meta-Material aided Sensing and Communications

Expectation on a new technology

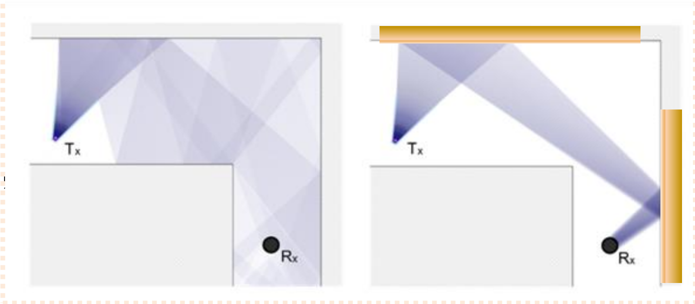
- Low cost in manufacture
- Easy and flexible deployment
- Compatible with 6G demands on communications and sensing

Reconfigurable Meta-surfaces



- Implemented by metamaterial
- Cost efficient in manufacture and deployment
- Control and customize favorable radio environments
- Provide high accuracy contact/contactless sensing with wireless data gathering
- So-called Reconfigurable Intelligent Surface

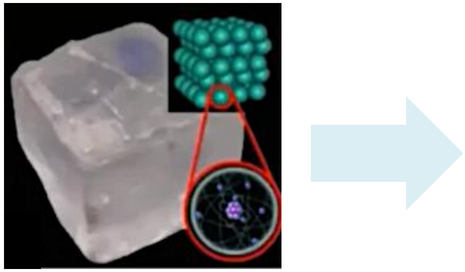
or Intelligent Reflecting Surface



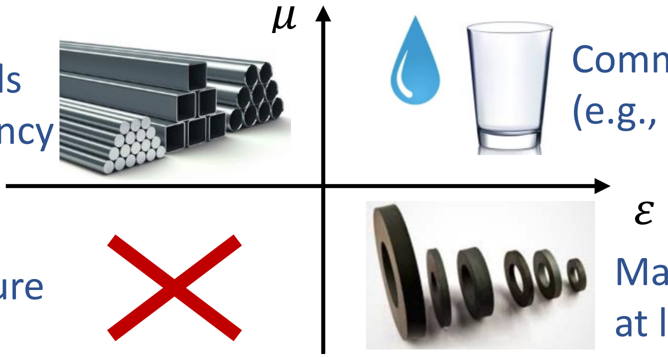
Introduction of Metamaterial

Natural Materials: Limited EM Wave Control Capability

- The *dielectric permittivity, ε,* and *magnetic conductivity, μ,* of materials determine the capability of controlling EM waves (e.g. reflection, refraction)
- Limited possibilities of atom arrangement of natural materials lead to limited available values of ε and μ, and thus limited capability to control EM waves



Atom arrangement has limited possibilities



Metal materials at light frequency

Common materials (e.g., water and glass)

Rare in nature

Magnetic materials at low frequency

Metamaterials: Powerful EM Wave Control Capability

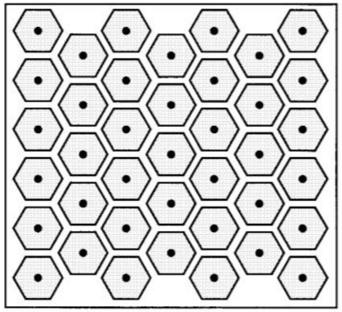
- Metamaterials are artificial structures that are non-existent in nature and can have arbitrary pair of (ε, μ)
- Two technology fields studying metamaterials – *Optics* and *Microwave*

History of Metamaterial Development

Veselago. Concept of Left-handed material

- $\epsilon < 0, \mu < 0$
- Negative refraction

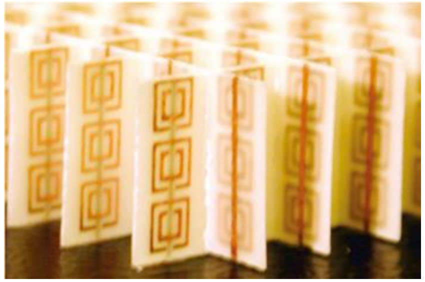
1968



Sievenpiper. Proposal of meta-surface

- Two-dimensional
- Simplify design and manufacturing

1999



D. R. Smith. Experimental verification

- Left-handed material

2001

1996 & 1999

Pendry. Realize -ε and -μ

- -ε: periodic array of metallic rods
- -μ: periodic array of split ring

2001

Sievenpiper.
Programmable metasurface

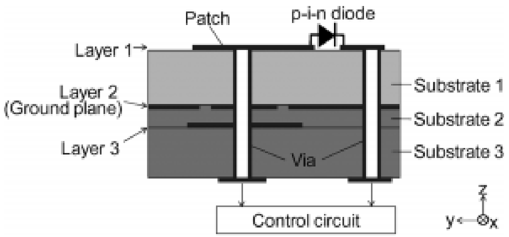
- Varactor
- 360^o reflection phase tuning

2006

Pendry, et al.
Transformation optics

- Design metamaterial with any ϵ and μ
- Enabling flexible control of EM wave

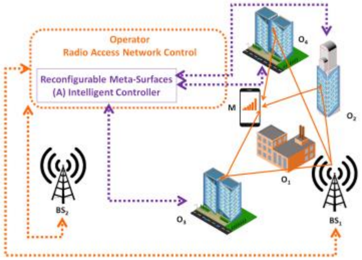
History of Metamaterial Development



H. Kamoda, et al.
Reconfigurable large reflectarray with PIN diodes

- Easy to control
- Millimeter wave

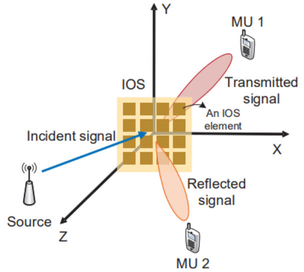
2011



M. D. Renzo, et al.
Proposal of reconfigurable intelligent surfaces

- Focus on reflection
- Extensive applications in wireless networks

2019



S. Zhang, et al.
Proposal of intelligent omni-surface

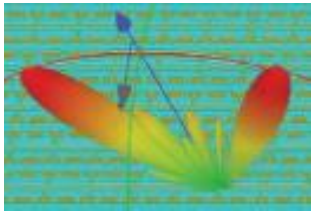
- Enabling dual function of reflection and transmission

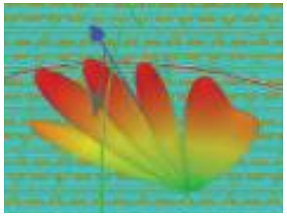
2020

2014

T. Cui, et al. Programmable metasurface with PIN diodes

- Simplify the design
- Digital coding

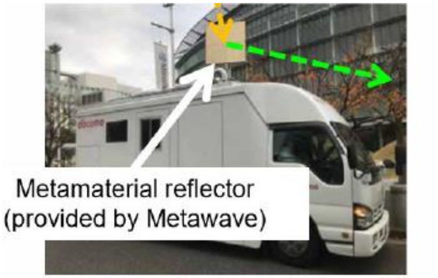




2019

NTT Docomo.
Protype of metamaterial reflector

- 10x increase in data rate

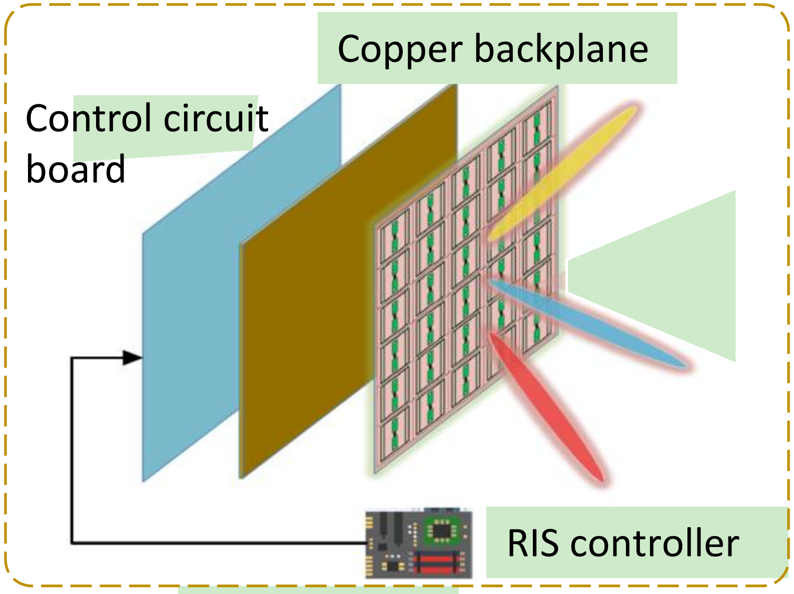


Metamaterial reflector (provided by Metawave)

Reconfigurable Intelligent Surfaces (RIS)

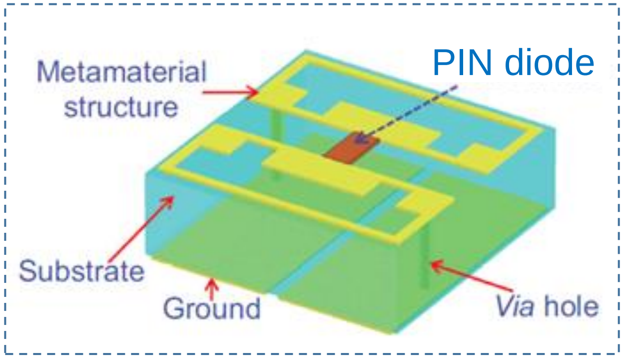
An ultra-thin metasurface composed of multiple layers

- **Outer layer**: A 2D-array of RIS elements; directly interact with incident signals.
- **Middle layer**: A copper plate; prevent the signal energy leakage.
- **Inner layer**: A printed circuit; connect the RIS elements to the RIS controller.



RIS element

- Low-cost sub-wavelength programmable metamaterial particle.
- Reflect incident RF signals and impose a controablle phase shift
- Working frequency: from sub-6 GHz to THz

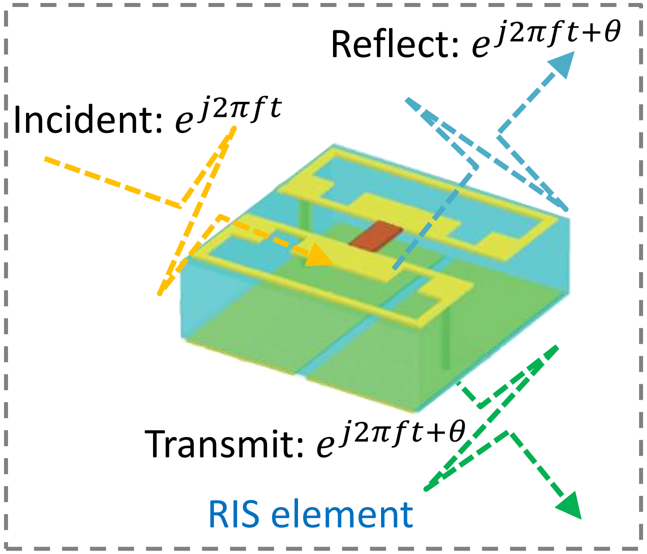


Example of a programmable metamaterial particle

Working Principle for Wireless Communications

RIS works as a beamformer

- Signals can be reflected or transmitted
- Phase shift of the radiation is controlled by PIN diodes' bias voltages (ON/OFF of the diode)
- Programming the ON/OFF of all diodes collectively realize different beamforming modes



Reflect: $e^{j2\pi ft+\theta}$

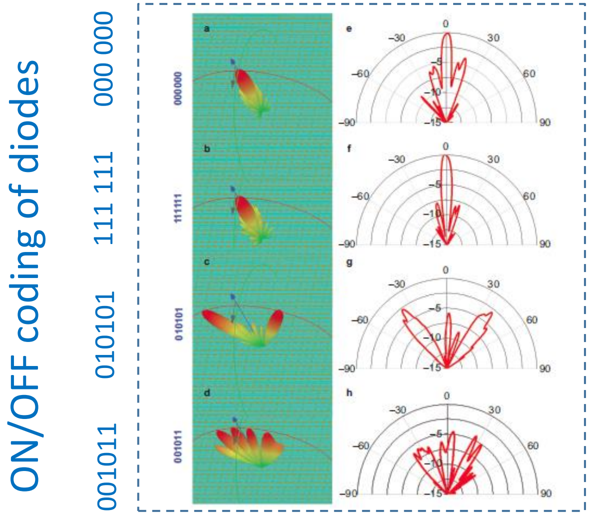
Incident: $e^{j2\pi ft}$

Transmit: $e^{j2\pi ft+\theta}$

RIS element

Advantage

- Cost efficiency: Analog beamforming, no extra RF chains needed for demodulation & modulation
- Energy Efficiency: No extra RF signals generation, energy saving



ON/OFF coding of diodes

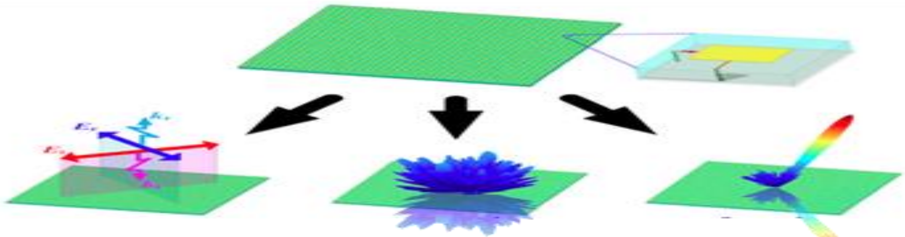
000 000

111 111

010101

001011

Reflected beam



Polarization

Scattering

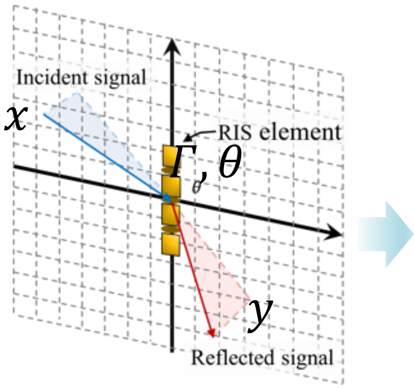
Focusing

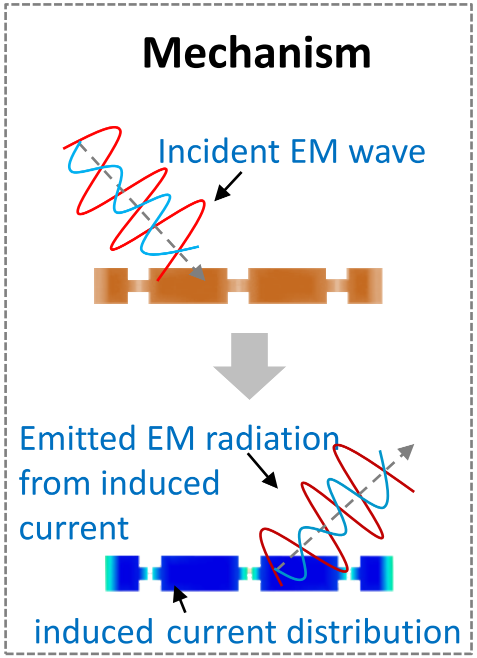
Signal Reflection Model

Model of reflected signal on an RIS element

$$y = \Gamma e^{j\theta} x$$

- $\Gamma \in [0,1]$: reflection amplitude
    - $\Gamma = 0$: absorbed
    - $\Gamma = 1$: fully reflected
- $\theta \in [0,2\pi]$: phase shift between incident and reflected signals.





- In practical systems, available phase shifts of an RIS element are discrete, due to limited number of PIN diodes (K PIN diodes $\Longrightarrow 2^K$ phase shifts).
- The parameters of an RIS element[1] are carefully designed so that the phase shifts have uniform intervals.

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[1]: e.g., shape of the metal patch and type of the PIN diodes

Channel Model

Rician Model

- User-RIS-BS links act as the dominant LoS component
- All other paths contributes the NLoS

$$\tilde{h}_{m,n} = \sqrt{\frac{\kappa}{\kappa + 1}}\boxed{h_{m,n}} + \sqrt{\frac{1}{\kappa + 1}}\boxed{\hat{h}_{m,n}},$$

Ratio of LoS to NLoS LoS NLoS

- Product of distance path loss

$$|h_{m,n}|^2 \propto d_{m,n}^{-\alpha} D_{m,n}^{-\alpha}$$

$$|\tilde{h}_{m,n}|^2 \propto d_{m,n}^{-\alpha} D_{m,n}^{-\alpha}$$

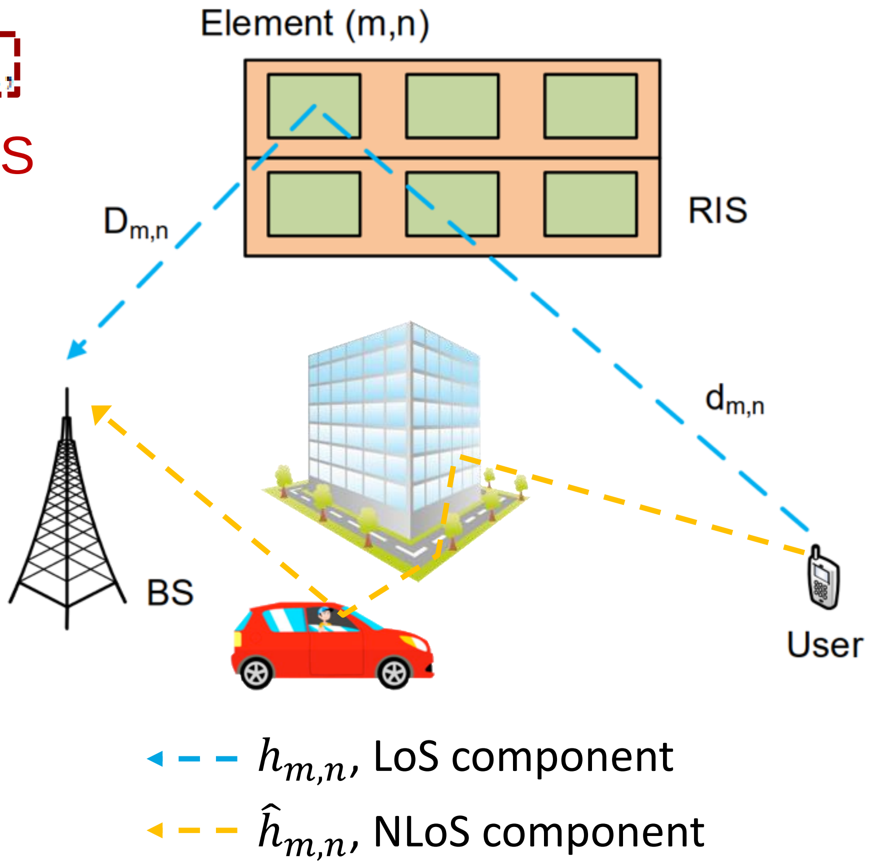
- Received signal

noise

$$y = \sum_{m,n} \underline{\Gamma e^{j\theta_{m,n}}}\, \underline{\tilde{h}_{m,n}} x + w$$

Reflection coefficient

Channel gain



Applications: Wireless Communications

Spectrum efficiency enhancement

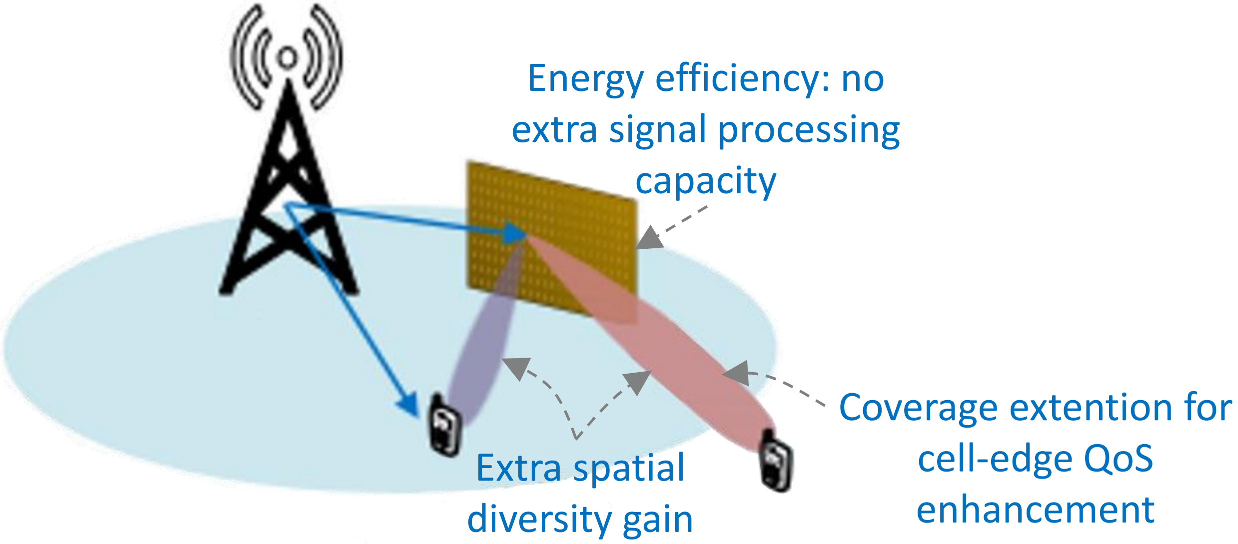
- RIS provides extra spatial diversity gain

Coverage extension

- RIS as a passive relay can assist APs to serve cell-edge users

Energy efficiency improvement

- RIS does not need extra energy-consuming hardware to be deployed



Energy efficiency: no extra signal processing capacity

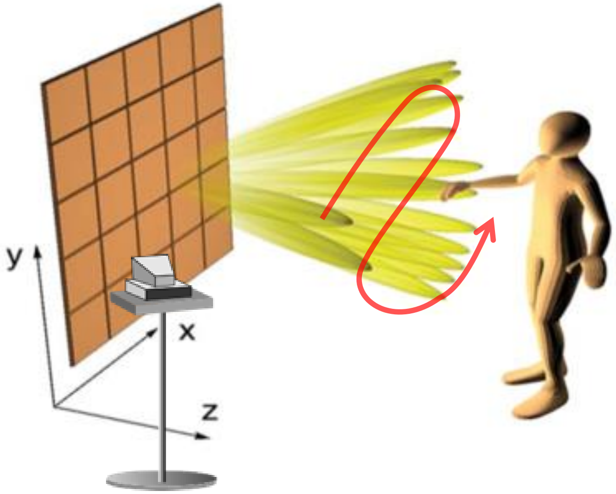
Extra spatial diversity gain

Coverage extention for cell-edge QoS enhancement

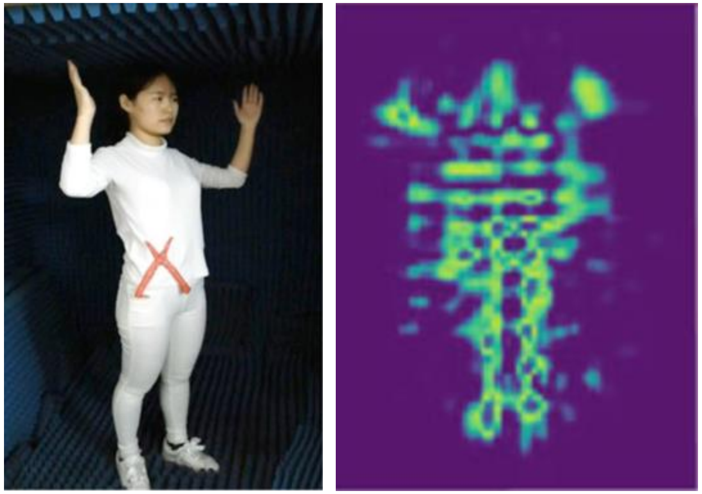
Applications: Radio Frequency Sensing

Indoor Localization and Recognition

- Enhance remote RF sensing by customize radio environments.
- Enable high accuracy indoor human and object localization and recognition

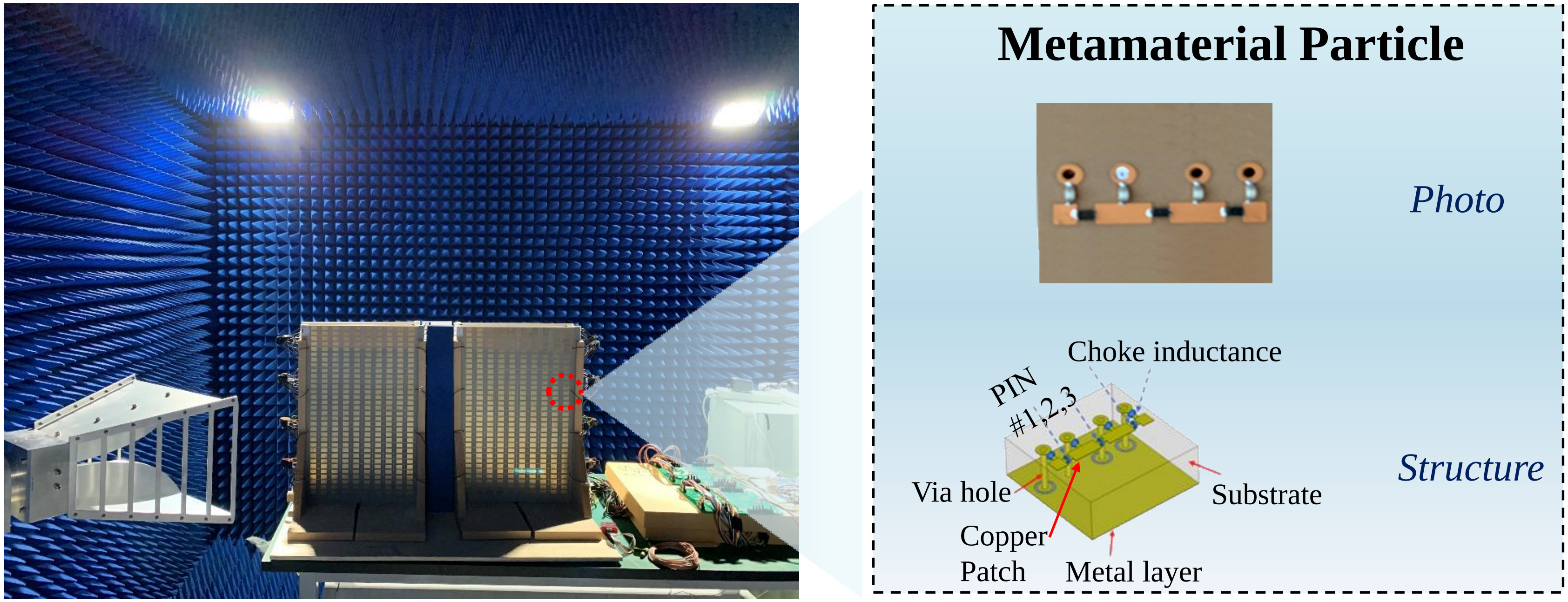


Customize signal beams for scanning human location



Customized radio environement for sensing human posture

Prototype of Metasurface



- **Size of metasurface:** 45×57×0.71 cm^3, total 640 metamaterial particles
- **Size of each metamaterial particle:** 2.87×1.42 cm^2
- **Total number of possible phase shifts**: 4
    - 2 of them are used, and have phase shifts with interval π
- **Working frequency:** 3.6 GHz

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* Photo shows the actual metasurface prototype used as the testbed in PKU lab.

RIS vs. Existing Technologies

Technology	Operating mechanism	Duplex	No. of transmit RF chains needed	Hardware cost	Energy consumption
RIS	Passive/Active, reflection	Full	0	Low	Low
Massive MIMO	Active, transmission/ reception	Half/full	N	Very high	Very high
Relay	Active, reception and transmission	Half/full	N	High	High
Backscatter	Passive, reflection	Full	0	Very low	Very low

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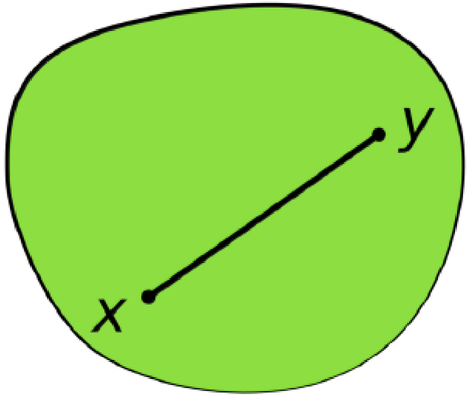
Optimization Theory

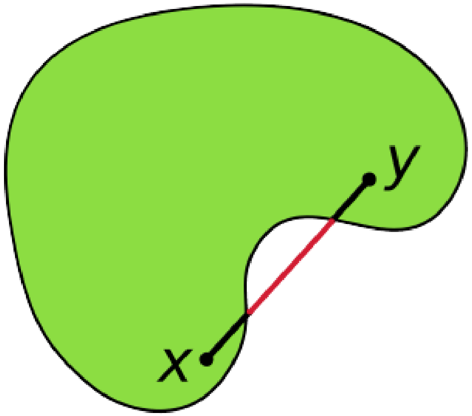
- Convex Set and Convex Functions
- Gradient Descent and Newton’s Method
- Duality and KKT Condition

Convex Set

- A set $S \subseteq \mathbb{R}^n$ is convex if for any $x, y \in S$ and any $\lambda \in [0,1]$, we have

$$\lambda x + (1-\lambda) y \in S$$





- There are convex sets and non-convex sets
- **Note:** There is no such thing as a “concave set”

Convex Function

- Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ satisfies

$$f(\lambda\mathbf{a} + (1 - \lambda)\mathbf{b}) \leq \lambda f(\mathbf{a}) + (1 - \lambda) f(\mathbf{b}),\ \forall\ \lambda \in [0, 1], \mathbf{a}, \mathbf{b} \in \mathbb{R}^n$$

then f is called a convex function. [or $-f$ is called a concave function]

- Intuitively, a convex function "holds water"

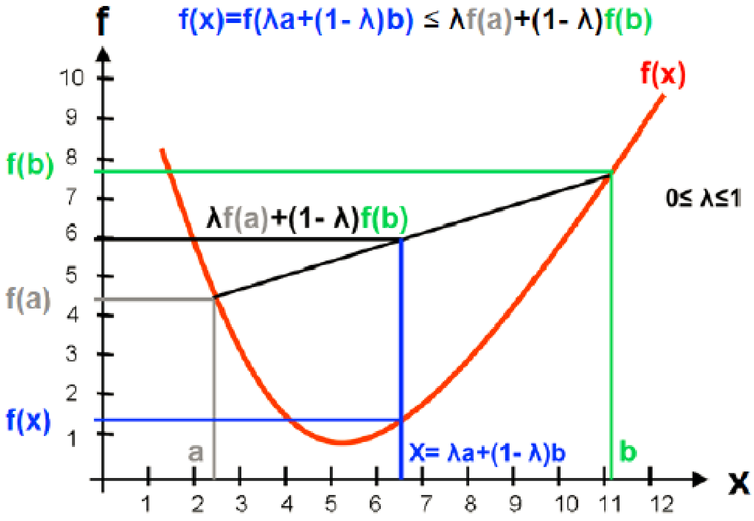


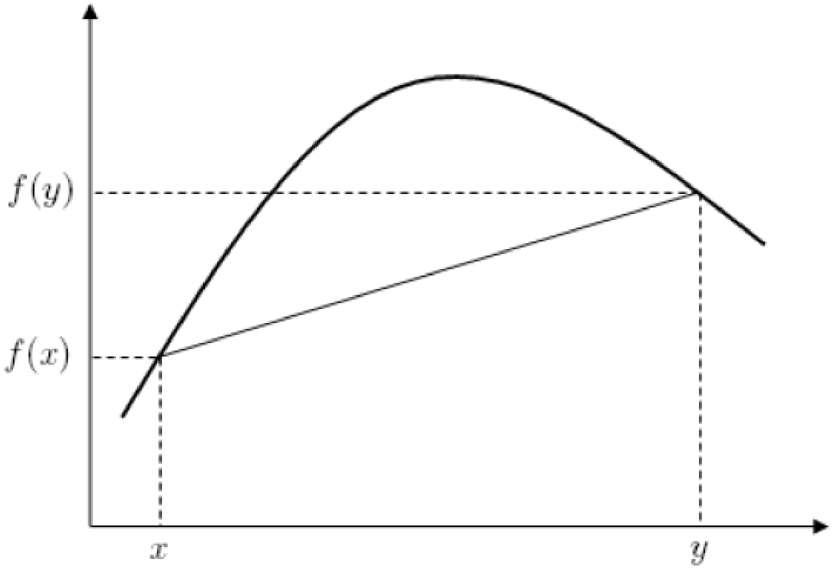
Figure: Illustration of a Convex Set [Moura 14]

Concave Function

- A function $f : \mathbb{R}^n \mapsto \mathbb{R}$ is called *concave* if for all $x, y \in \mathbb{R}^K$ and for all $\lambda \in [0, 1]$, we have

$$f[\lambda x + (1 - \lambda)y] \geq \lambda f(x) + (1 - \lambda) f(y).$$

- **Question:** A linear function is convex or concave function?



Convex Optimization

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & x \in X \end{array}$$

- Here f is continuously differentiable, X is a convex set
- Convex set X means we allow the following types of constraints
  1. $g(x) \leq 0$ where $g(x)$ is a convex function
  2. $h(x) = 0$ where $h(x)$ is an affine function: $Cx + d = 0$

Convex means local minimum = global minimum

Algorithms to Find Optimum

- Now we have settled the question of when global min = local min
- We are then interested in finding such "global min"
- **Easiest way**: Simply solve $\nabla f(\mathbf{x}) = 0$!
- Suppose $\nabla f(\mathbf{x}) = 0$ is not easy, don't know how to solve
- Then what?

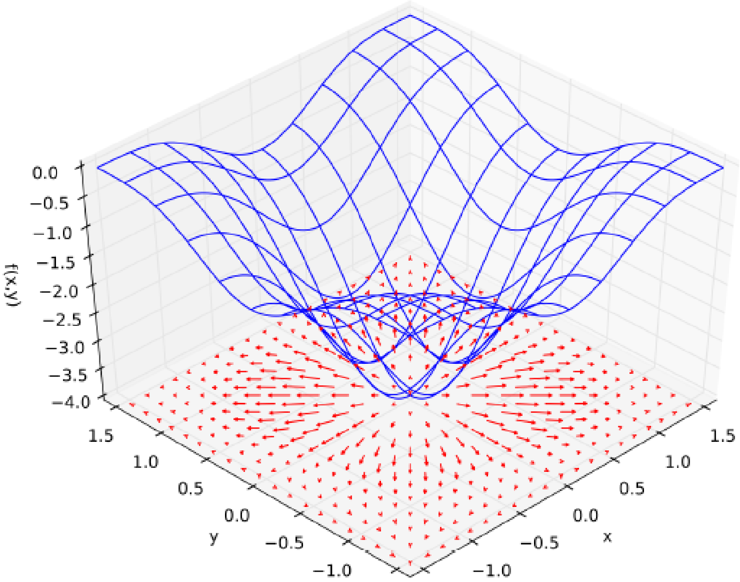


Figure: The gradients of a function (Wikipedia: Gradient)

Gradient Descent Method

- If $\nabla f(\mathbf{x}) = 0$, then $\mathbf{x}$ is a candidate solution (satisfying first-order sufficient condition); Done
- If $\nabla f(\mathbf{x}) \neq 0$, there is an interval $(0, \delta)$ of stepsizes such that

$$f(\mathbf{x} - \alpha \nabla f(\mathbf{x})) < f(\mathbf{x}), \ \forall \ \alpha \in (0, \delta).$$

- Show this using Mean Value Theorem [on board]?
- More generally, if a given direction $\mathbf{d}$ that is with obtuse angle with $\nabla f(\mathbf{x})$

$$\langle \nabla f(\mathbf{x}), \mathbf{d} \rangle < 0$$

there is an interval $(0, \delta)$ of stepsizes such that

$$f(\mathbf{x} + \alpha \mathbf{d}) < f(\mathbf{x}), \ \forall \ \alpha \in (0, \delta).$$

Iterative Descent Method

$$\mathbf{x}^{r+1} = \mathbf{x}^r + \alpha_r \mathbf{d}^r, \; r = 0, 1, \cdots$$

where, if $\nabla f(\mathbf{x}^r) \neq 0$, the direction $\mathbf{d}^r$ satisfies $\nabla f(\mathbf{x}^r)\mathbf{d}^r < 0$, and α^r is a positive stepsize

- General Case: Gradient descent methods

$$\mathbf{x}^{r+1} = \mathbf{x}^r - \alpha_r \mathbf{D}^r \nabla f(\mathbf{x}^r), \; r = 0, 1, \cdots$$

  where $\mathbf{D}^r$ is a positive definite matrix

- Special case I: Steepest descent

$$\mathbf{x}^{r+1} = \mathbf{x}^r - \alpha_r \nabla f(\mathbf{x}^r), \; r = 0, 1, \cdots$$

- Special case II: Newton's method

$$\mathbf{x}^{r+1} = \mathbf{x}^r - \alpha_r \left(\nabla^2 f(\mathbf{x}^r)\right)^{-1} \nabla f(\mathbf{x}^r), \; r = 0, 1, \cdots$$

Shortcoming of Gradient Method

However, in practice steepest descent may have slow convergence

Figure: The Steepest Descent (ERASIP: DSPHumour)

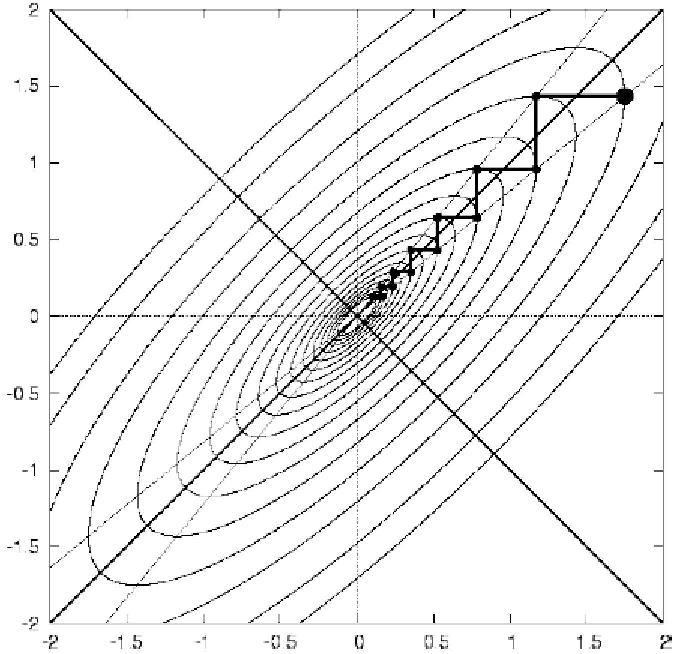


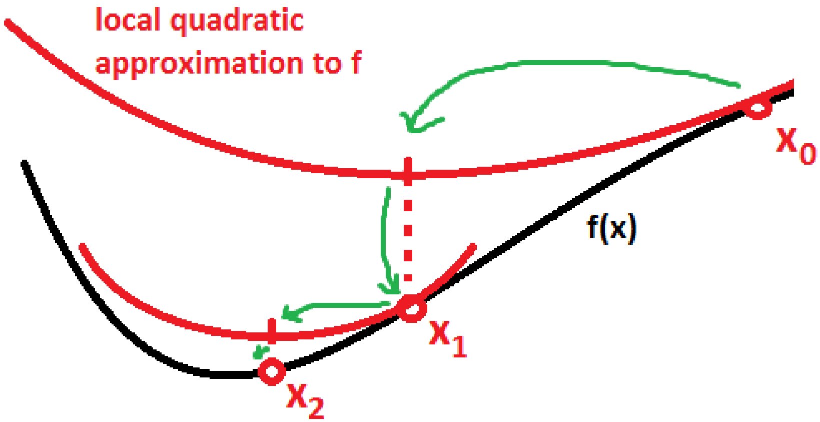
Figure: The Steepest Descent in Practice (Komarix.org)

Newton's Method

- Newton's method: generally fast convergence
  - Basically it treats the objective (locally) as a quadratic problem around $\mathbf{x}^r$

$$f(\mathbf{x}) \approx f(\mathbf{x}^r) + \langle \nabla f(\mathbf{x}^r), \mathbf{x} - \mathbf{x}^r \rangle + \frac{1}{2}(\mathbf{x} - \mathbf{x}^r)^T \nabla^2 f(\mathbf{x}^r)(\mathbf{x} - \mathbf{x}^r)$$

  - Question: how many iterations does it take for Newton method to minimize a quadratic function f?
  - Caution: very difficult to make it numerically stable, needs more information than the steepest descent method



Lagrangian Multiplier

$$\begin{array}{lll} \text{minimize} & f(x) & \\ \text{subject to} & h_i(x) = 0, & i = 1, \cdots, m \\ & g_j(x) \leq 0, & j = 1, \cdots, n \end{array}$$

- **Reminder**: The problem is called convex problem if
  1. $f(x)$ is a convex function
  2. $h_i(x)$ is an affine function, i.e., $h_i(x) = Ax + b$
  3. $g_j(x)$ is a convex function
- The Lagrangian can be formed using the Lagrangian multipliers $\lambda_i \geq 0$ and $\nu_i \in \mathbb{R}$

$$L(x, \lambda, \nu) = f(x) + \sum_{j=1}^{n} \lambda_j g_j(x) + \sum_{i=1}^{m} \nu_i h_i(x)$$

Duality

- The Lagrangian dual function

$$L^*(\lambda, \nu) = \inf_{x \in X} L(x, \lambda, \nu) = \inf_{x \in X} f(x) + \sum_{j=1}^{n} \lambda_j g_j(x) + \sum_{i=1}^{m} \nu_i h_i(x)$$

- The Dual Problem

$$\max_{\lambda, \nu} \quad L^*(\lambda, \nu), \quad \text{s.t. } \lambda \geq 0$$

- λ_i and ν_i's can be viewed as "prices" for violating the constraints
- Let f^* be the optimal value of $f(x)$
- The Lagrangian dual L^* is
  1. A concave function: even when the original problem is not convex
  2. A lower bound: for $\lambda \geq 0$, $L^*(\lambda, \nu) \leq f^*$

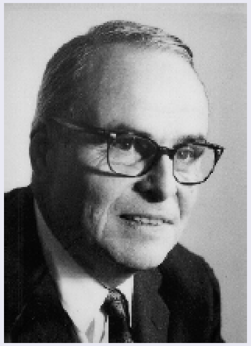
Duality

- Let d^* be the optimal objective of the dual
- Weak duality: $d^* \leq f^*$
  1. Always true
  2. Non-trivial lower bound for hard problems
  3. Useful in approximation algorithms
- Strong duality: $d^* = f^*$
  1. Does not hold in general
  2. If holds, sufficient to solve the dual
  3. How to check if it holds?
- Constraint qualification
  1. Normally true for convex problems
  2. True if the problem is convex; And it is strictly feasible, i.e. there exists a $x \in X$ such that
     $$h_i(x) = 0, \quad g_j(x) < 0$$
  3. The above condition is known as the Slater's condition

KKT Condition: When to Stop?

$$
\begin{aligned}
\text{minimize} \quad & f(x) \\
\text{subject to} \quad & h_i(x) = 0, \quad i = 1, \cdots, m && (1) \\
& g_j(x) \le 0, \quad j = 1, \cdots, n && (2)
\end{aligned}
$$

Any optimal and dual pairs $\tilde{x}$ and $(\tilde{\lambda}, \tilde{\nu})$ must satisfy



Albert Tucker

$$\nabla f(\tilde{x}) + \sum_{j=1}^{n} \tilde{\lambda}_j \nabla g_j(\tilde{x}) + \sum_{i=1}^{m} \tilde{\nu}_i \nabla h_i(\tilde{x}) = 0_{K\times 1}$$

$$g_j(\tilde{x}) \le 0, \forall j = 1, ..., n, \quad \text{(primal feasibility)}$$

$$h_i(\tilde{x}) = 0, \forall i = 1, ..., m, \quad \text{(primal feasibility)}$$

$$\tilde{\lambda}_j \ge 0, \forall j = 1, ..., n, \quad \text{(dual feasibility)}$$

$$g_j(\tilde{x}) \times \tilde{\lambda}_j = 0, \forall j \quad \text{(complementarity).}$$

Harold Kuhn

Barrier Function

reformulation of (1) via indicator function:

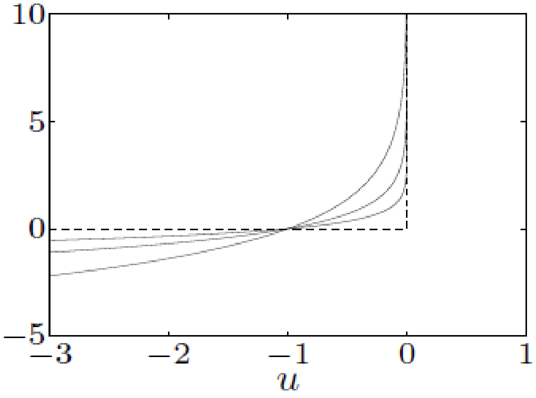
$$\begin{array}{ll}\text{minimize} & f_0(x) + \sum_{i=1}^m I_-(f_i(x)) \\ \text{subject to} & Ax = b\end{array}$$

where $I_-(u) = 0$ if $u \leq 0$, $I_-(u) = \infty$ otherwise (indicator function of $\mathbf{R}_-$)

approximation via logarithmic barrier

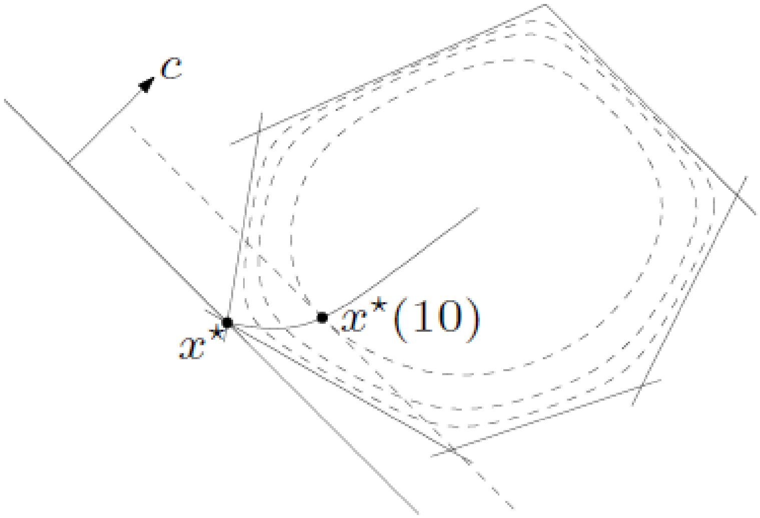
$$\begin{array}{ll}\text{minimize} & f_0(x) - (1/t)\sum_{i=1}^m \log(-f_i(x)) \\ \text{subject to} & Ax = b\end{array}$$

- an equality constrained problem
- for $t > 0$, $-(1/t)\log(-u)$ is a smooth approximation of I_-
- approximation improves as $t \to \infty$



Interior Point Method

```
given strictly feasible $x$, $t := t^{(0)} > 0$, $\mu > 1$, tolerance $\epsilon > 0$.
repeat
    1. Centering step. Compute $x^\star(t)$ by minimizing $tf_0 + \phi$, subject to $Ax = b$.
    2. Update. $x := x^\star(t)$.
    3. Stopping criterion. quit if $m/t < \epsilon$.
    4. Increase $t$. $t := \mu t$.
```



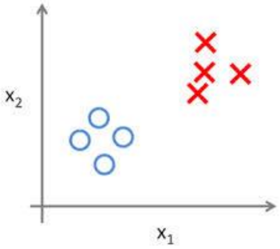
Learning Methods

- Classical Machine Learning
- Deep Learning
- Reinforcement Learning

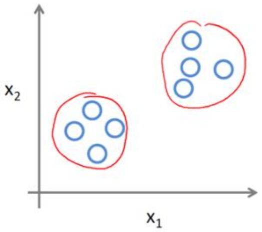
Classical Machine Learning

"Computers: learn without being explicitly programmed"

- Types:
  - Supervised Learning:
    - Example inputs (features) and their desired outputs (labels)
    - Goal: learn a general rule that maps inputs to outputs
    - SVM, neural networks, etc.

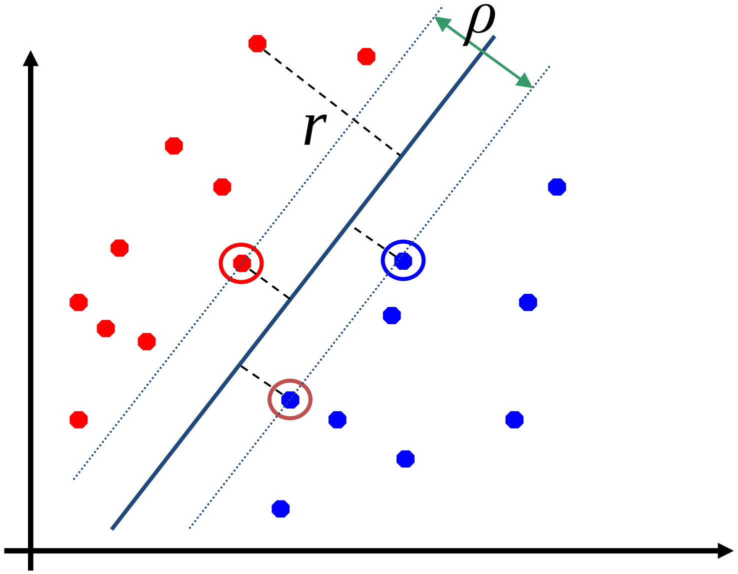


  - Unsupervised Learning:
    - No labels
    - Find structure in its input
    - Goal: discover hidden patterns in data
    - Clustering, K-means, etc.



Supervised Learning: SVM

- Distance from sample x_i to the separator: r
- Support vectors: samples closest to the hyperplane
- Margin ρ: the distance between support vectors
- Objective: maximize the margin ρ



$$r = \frac{y_i(w^T x_i + b)}{|w|} = \frac{1}{|w|}$$

$$\rho = \frac{2}{|w|}$$

$$y = -1 : w^T x_i + b \le -\frac{\rho}{2}$$

$$y = 1 : w^T x_i + b \ge \frac{\rho}{2}$$

Supervised Learning: Applications

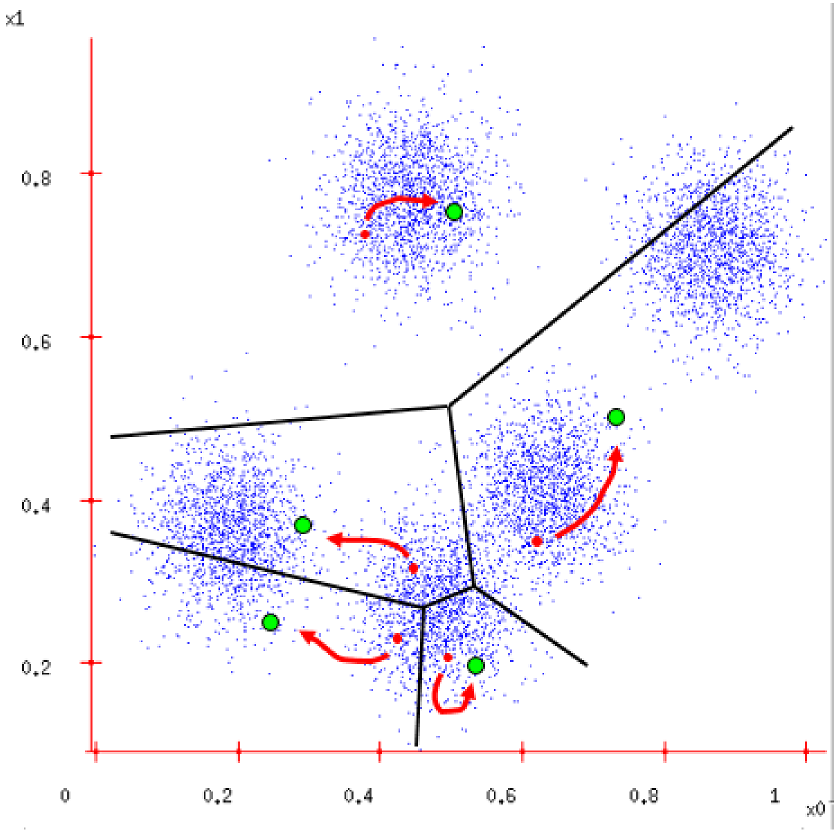
- The best performers for a number of classification tasks ranging from text to genomic data.

- Complex data types beyond feature vectors (e.g. graphs, sequences, relational data) by designing kernel functions for such data.

- Extend to a number of tasks such as regression, principal component analysis, etc.

Unsupervised Learning: K-Means

- Ask user how many clusters they'd like. (e.g. *k*=5)
- Randomly guess *k* cluster center locations
- Each data point: find out which center it's closest to
- Each center: find the centroid of the points it owns
- Change center
- Repeat until terminated



Unsupervised Learning: Applications

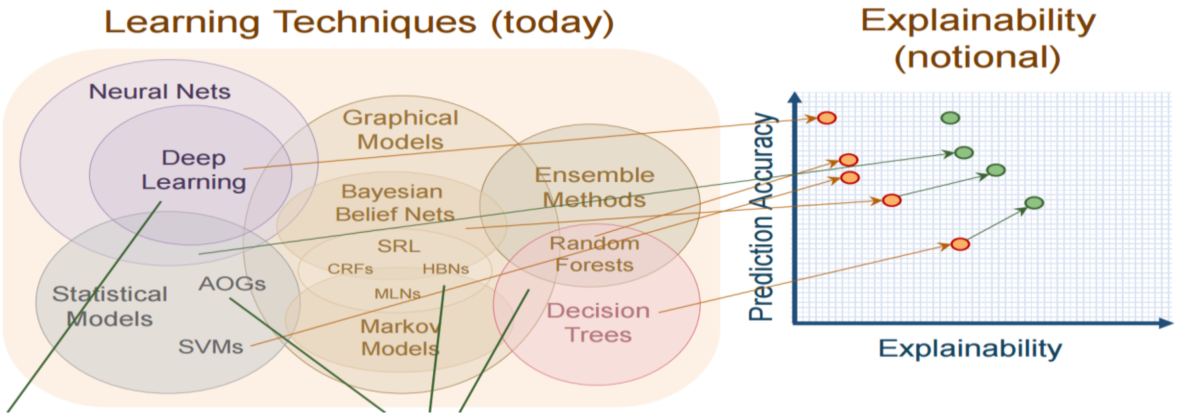
- Data mining

- Acoustic data in speech understanding to convert waveforms into one of k categories (known as Vector Quantization or Image Segmentation)

- Also used for choosing color palettes on old fashioned graphical display devices and Image Quantization

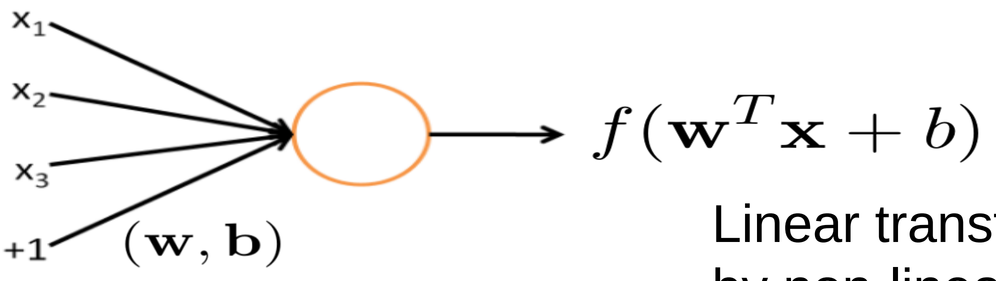
Deep Learning: Motivations

- Classic Methods
  - Do not have a lot of data, or
  - Training data have categorical features
  - A more explainable model
  - A high run-time speed
- Deep Learning
  - A lot of training data of the same or related domain
  - Improve Domain Adaptation
  - Appropriate scaling and normalization have to be done
  - Much slower

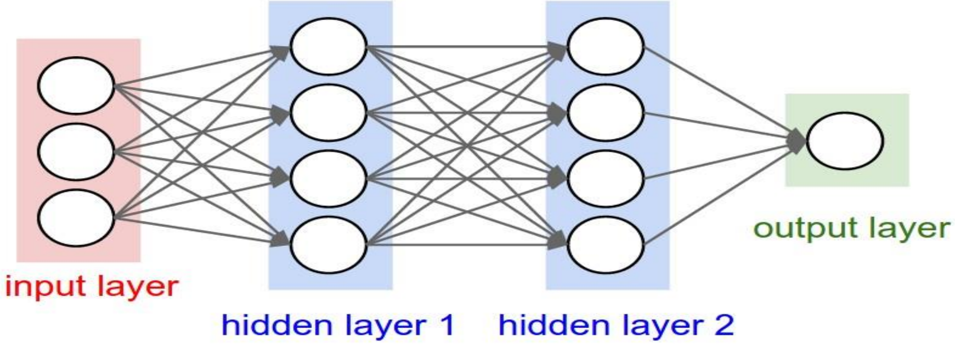


Deep Learning: Basic Idea

- Add Hidden Layers in Neural Networks



Linear transformation followed by non-linear rectification



☐ More parameters
☐ More non-linear parts

Typical Deep Neural Networks

- Convolutional Neural Networks (CNNs)
- Recurrent Neural Networks (RNNs)
- Deep Belief Networks

Convolutional Neural Networks (CNNs)

INPUT IMAGE

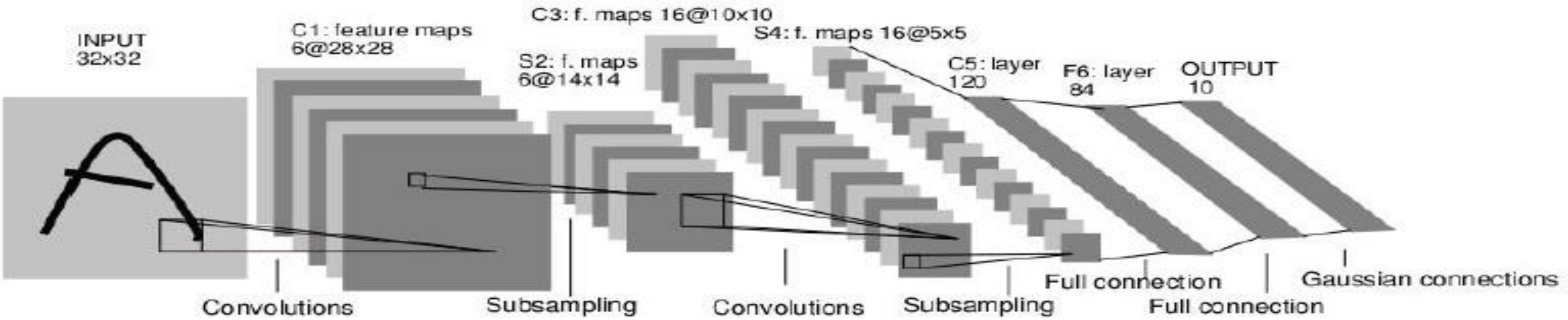
CONVOLUTION (LEARNED)

NON-LINEAR RECTIFIER

POOLING

FEATURE MAPS

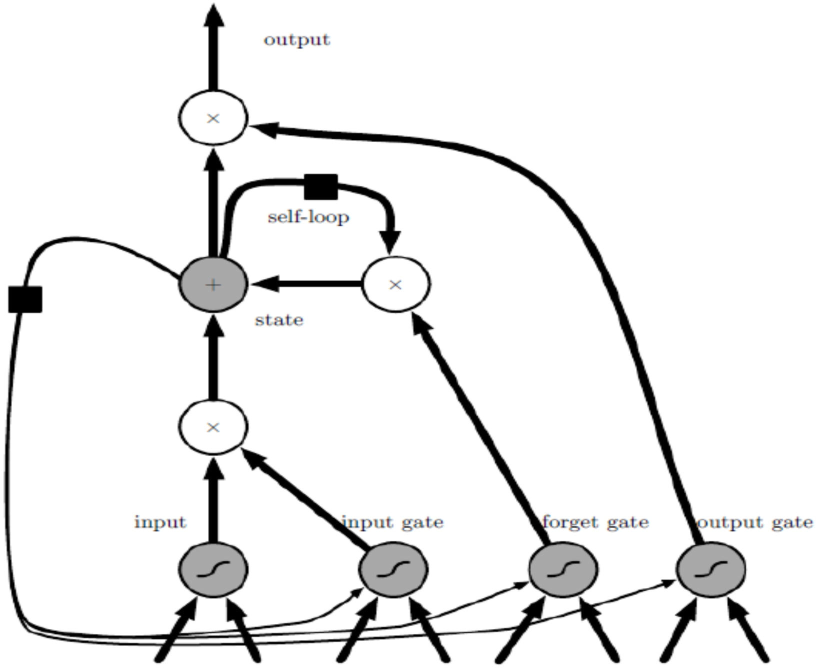
Work well in image processing!



[4] LeCun, Yann. "LeNet-5, convolutional neural networks". Retrieved Nov. 2013.

Recurrent Neural Networks (RNNs)

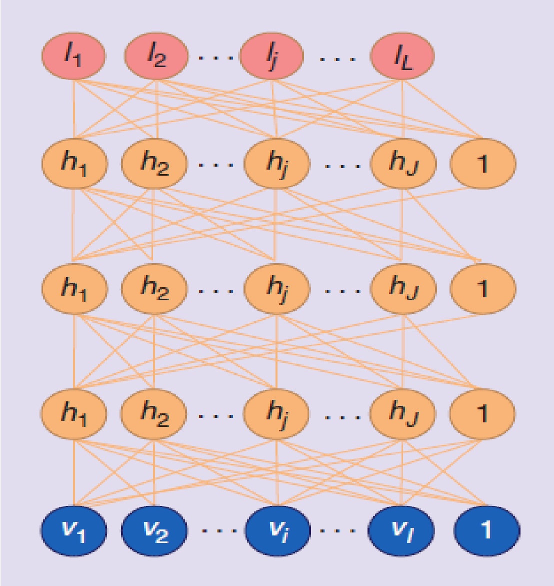
- Produce an output at each time step and have recurrent connections between hidden units
    - Long Short-Term Memory

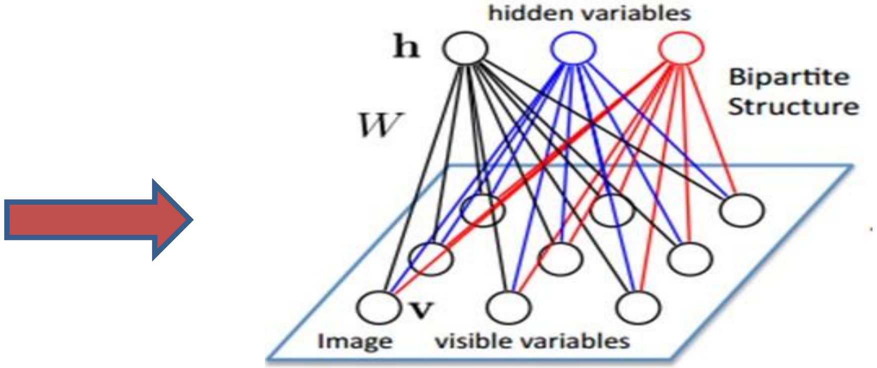


- Unconstrained handwriting recognition (Graves et al., 2009),
- Speech recognition (Graves et al., 2013; Graves and Jaitly, 2014)
- Handwriting generation (Graves, 2013),
- Machine translation (Sutskever et al., 2014)
- Image captioning (Kiros et al., 2014;Vinyals et al., 2014; Xu et al., 2015)
- Parsing (Vinyals et al., 2014a).

Deep Belief Networks

- Each link associates with a probability
- Parametric





The energy of the joint configuration:

$$E(\mathbf{v},\mathbf{h};\theta) = -\sum_{ij} W_{ij} v_i h_j - \sum_{i} b_i v_i - \sum_{j} a_j h_j$$

$\theta = \{W, a, b\}$ model parameters.

- Applied in clustering

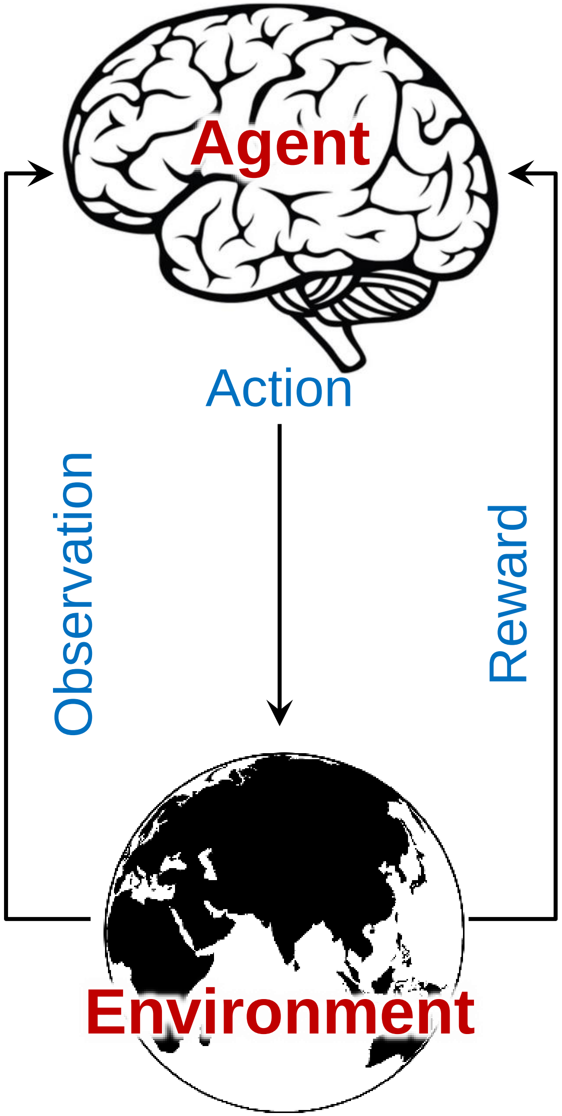
[5] G. E. Hinton, S. Osindero, and Y. W. Teh, "A Fast Learning Algorithm for Deep Belief Nets", *Neural Computation*. Vol. 18, No. 7, pp.1527–1554, 2006.

Comparison

	Similarities	Differences
Convolutional Neural Networks	1. Multiple Layers 2. Use Back-propagation Algorithm for training 3. Can be combined together to create more powerful networks	1. More suitable for data with grid structures 2. Much fewer parameters 3. Very efficient training with GPUs
Recurrent Networks		1. Having memory of past (suitable for tasks like speech recognition) 2. Not able to take big input such as images or videos
Deep Belief Networks		1. Generative model (can generate realistic looking data after initializing at random variable) 2. Used much less due to inefficiency

Reinforcement Learning

- **Agent** —— An intelligent individual
- **Environment** —— Changes with the agent's action, then provides reward
- The agent observes the environment, takes action, and gets reward iteratively
- **Target of the agent** —— To maximize the total reward in the long run
- In case of full observation:
  - System states can be modelled as **Markov Decision Process (MDP)**



Markov Decision Process

- A Markov decision process further includes action in the Markov reward process, written as a tuple $\langle \mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma \rangle$
- $\mathcal{S}$ is a **finite set of the states** that have Markov property:

$$\mathbb{P}[S_{t+1} \mid S_t] = \mathbb{P}[S_{t+1} \mid S_1, ..., S_t]$$

  - Any finite set of discrete states $\xrightarrow[\text{transformed}]{\text{can be}}$ Markov states
- $\mathcal{A}$ is a **finite set of the actions**, from which the agent can choose to perform at each current state
- $\mathcal{P}$ is the **state transition probability matrix**, defined as the probability of state transition based on a given action:

$$\mathcal{P}_{ss'}^{a} = \mathbb{P}[S_{t+1} = s' \mid S_t = s, A_t = a]$$

Markov Decision Process

- A Markov decision process further includes action in the Markov reward process, written as a tuple $\langle \mathcal{S}, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma \rangle$

- $\mathcal{R}$ is a **reward function**, showing the average reward of the next step when the current state is S_t , given as

$$\mathcal{R}_s = \mathbb{E}\left[R_{t+1} \mid S_t = s\right]$$

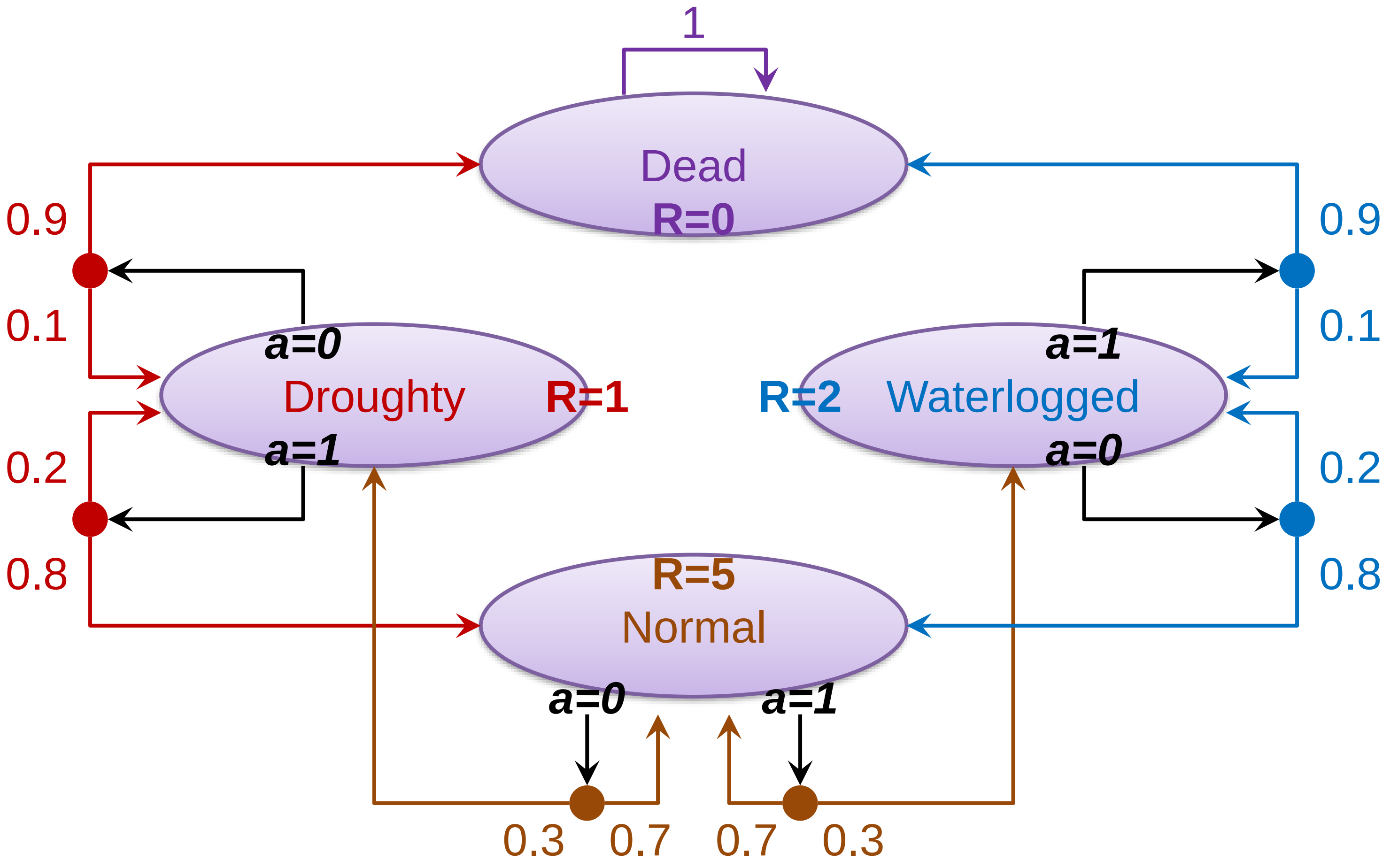
- γ is a **discount factor**, which is used to weaken the reward of future, given by $\gamma \in [0, 1]$, avoiding infinite returns in cyclic state transitions

- Denote accumulative future reward as:

$$G_t = R_{t+1} + \gamma R_{t+2} + \ldots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

Markov Decision Process: Example

- Cultivating the flower by deciding whether to water it (***a=1*** for watering and ***a=0*** for non-watering)



Policy and Value Function

- **Policy** is the agent's behavior
- It is a ***map*** from ***state*** to ***action***
- Deterministic: $a = \pi(s)$ Stochastic: $\pi(a|s) = \mathbb{P}[A_t = a|S_t = s]$
- **Value function** is a prediction of future reward
- Used to evaluate the goodness/badness of states
- Defined as the average accumulative future reward from the current state based on the given policy π:
    - **State value function**: $v_\pi(s) = \mathbb{E}_\pi\left[G_t \mid S_t = s\right]$
    - **Action value function**: $q_\pi(s, a) = \mathbb{E}_\pi\left[G_t \mid S_t = s, A_t = a\right]$

Optimal Policy

- What is the optimal policy?
  - A policy that leads to the highest value for any state:

$$\pi \geq \pi' \text{ if } v_\pi(s) \geq v_{\pi'}(s), \forall s$$

- **Theorem**: For any Markov decision process, there exists an optimal policy π_* that is better than / equal to any other policy:

$$\pi_* \geq \pi, \forall \pi$$

- There is always a **deterministic optimal policy** for any MDP, given as

$$\pi_*(a|s) = \begin{cases} 1 & \text{if } a = \underset{a \in \mathcal{A}}{\text{argmax}}\, q_*(s,a) \\ 0 & otherwise \end{cases}$$

- Non-linear, no closed solution, many iterative methods

Q-Learning

Off-policy learning

- Experience from behavior $\mu(a|s)$
- E.g., learning from existing chess movement records

- A slightly different update function

$$Q(S,A) \leftarrow Q(S,A) + \alpha \left(R + \gamma \max_{a'} Q(S',a') - Q(S,A) \right)$$

- Use the best successor action instead of the action form the behavior to update the current Q(S,A)

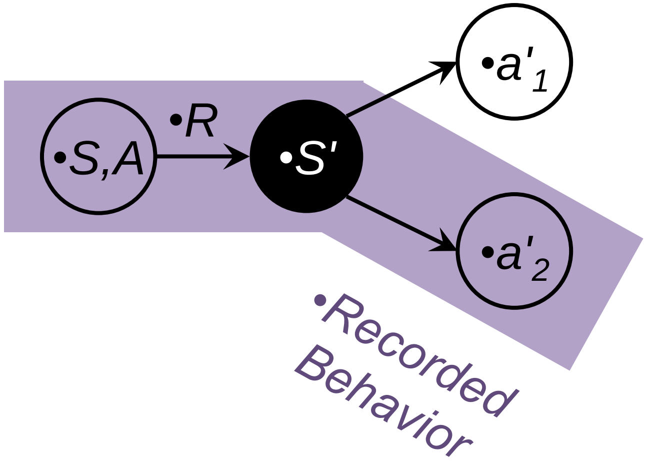


Table of Contents

Goals and Challenges in RIS-aided Cellular Communication

Goals

- Higher energy efficiency
- Higher capacity / Lower interference
- Larger coverage

Challenges

- How to design the number of phase shifts?
- How to deploy the RIS (orientation and location)?
- How does the size of RIS influence the performance?
- How to design the RIS configuration (phase shift)?
- How to coordinate multi-user access?

Case Study I: Limited Phase Shifts Effect

RIS assisted Communications with Limited Phase Shifts:

How Many Phase Shifts Are Enough?

H. Zhang, et al, "Reconfigurable Intelligent Surfaces assisted Communications with Limited Phase Shifts: How Many Phase Shifts Are Enough?" IEEE Transactions on Vehicle Technology, vol. 69, no. 4, pp. 4498-4502, Apr. 2020.

Motivations and Contributions

Problems

- Lack of the performance limit analysis of RIS-aided cellular communication.
- Most works assume continuous phase shifts, which are hard to be implemented in practice.
- It is worthwhile to study the impact of the limited phase shifts on the achievable data rate.

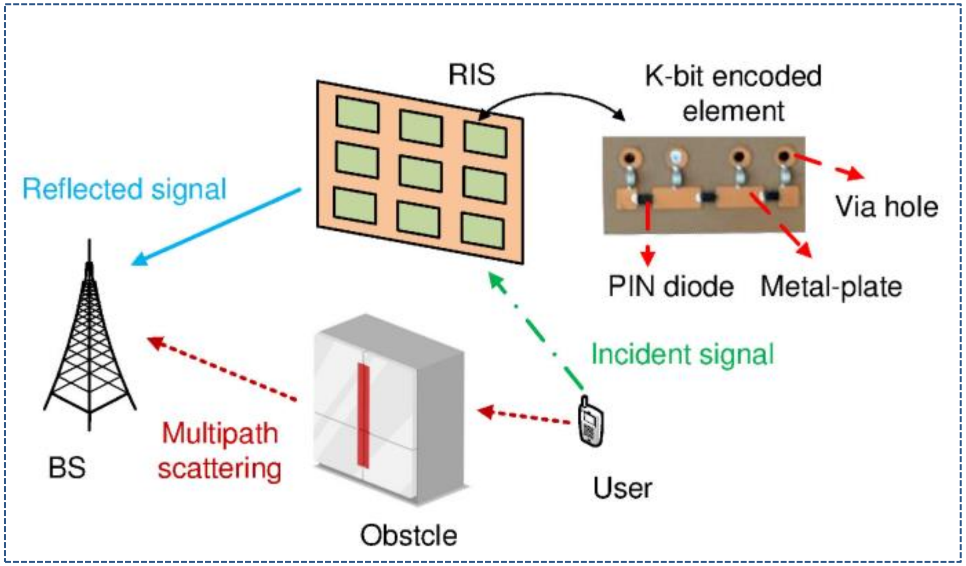
Contributions

- We provide an analysis on the achievable data rate with continuous phase shifts of the RIS, to evaluate the performance limits of the RIS assisted communications.
- We discuss how the limited phase shifts influence the data rate based on the derived achievable data rate expression.

System Model

System Description

- Single cell uplink network
- LoS between the BS and the user is blocked
- RIS to reflect user's signal to BS
- Phase shift of RIS element
    - *K*-bit quantized, i.e., 2^K uniformly-spaced



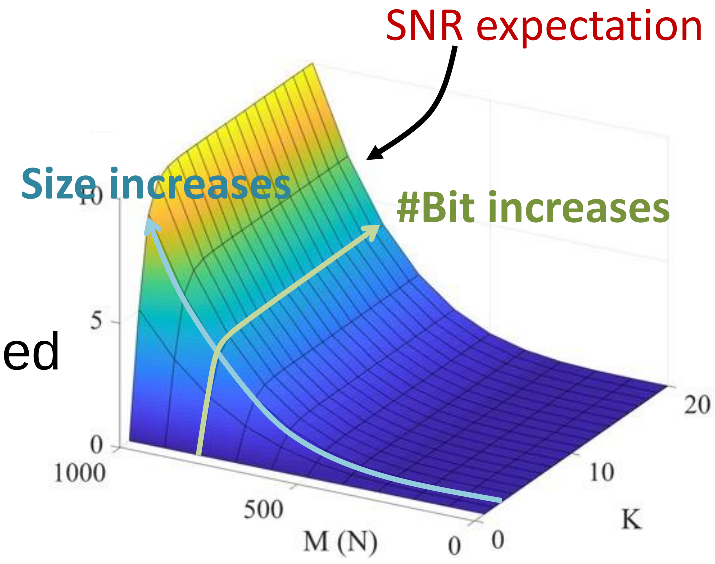
- The uplink data rate of the user can be expressed by

$$\mathbb{E}\left[\log_2(1+\gamma)\right] \approx \log_2\left(1+\frac{\eta_{LoS}}{\kappa+1}MN+\frac{\kappa\eta_{NLoS}}{\kappa+1}\sum_{m,m',n,n'} e^{-j[\phi_{m,n}-\phi_{m',n'}+\theta_{m,n}-\theta_{m',n'}]}\right)$$

LoS path loss NLoS path loss Channel phases Phase shifts

- Ideally, channel phase and phase shift corresponding to each RIS element should satisfy $\theta^*_{m,n} + \phi_{m,n} =$ Constant, to max data rate

Analysis on Number of Phase Shifts


SNR expectation

Size increases

#Bit increases

- Phase shifts errors

$$\delta_{m,n} = \underset{\text{Continuous}}{\underline{\theta^*_{m,n}}} - \underset{\text{Discrete}}{\hat{\theta}_{m,n}}.$$

- With *K* bit quantized, the errors can be bounded by

$$-\frac{2\pi}{2^{K+1}} \leq \delta_{m,n} < \frac{2\pi}{2^{K+1}}$$

- SNR expectation with limited phase shifts

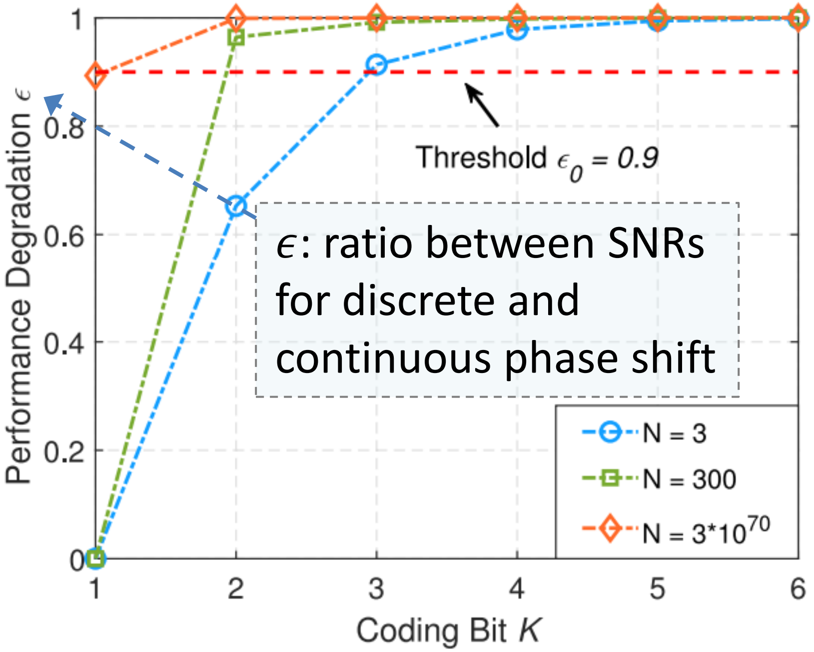
$$\boxed{\mathbb{E}[\hat{\gamma}] \geq \frac{\eta_{NLoS}}{\kappa+1} MN + \frac{\kappa\eta_{LoS}}{\kappa+1} M^2 N^2 \cos^2\left(\frac{2\pi}{2^{K+1}}\right)}$$

- Therefore, the expected received SNR given RIS with discrete phase shifts satisfies that

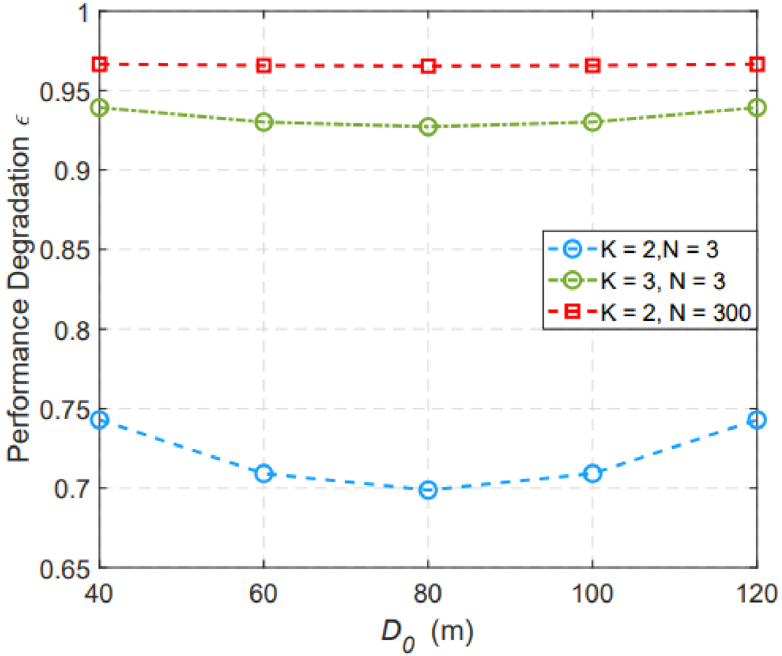
$$\mathbb{E}[\text{SNR}] \propto (\text{RIS's size})^2 \cdot \cos^2(\frac{2\pi}{2^{(\#\ \text{Quantized bits})+1}})$$

- Increase the RIS's size can help allieivate the SNR loss due to small K.

Simulation Results



ϵ: ratio between SNRs for discrete and continuous phase shift



- Required quantized bits decrease as the number of RIS elements grows, and 1 bit is enough when the RIS size goes to infinity
- We can easily observe that the data rate degradation will decrease first and then increase as the distance between the RIS and the BS increases given RIS size and quantized bit

Case Study II: Size Effect

Reconfigurable Intelligent Surface assisted Multi-user Communications:

How Many Reflective Elements Do We Need?

H. Zhang et al, "Reconfigurable Intelligent Surface assisted Multi-user Communications: How Many Reflective Elements Do We Need?" IEEE Wireless Communications Letters, early access.

Motivations and Contributions

Problems

- Most works focus on the phase shift optimization/analysis in RIS assisted wireless communications
- The size of the RIS will also influence the system sum rate
- It is worthwhile to study how many RIS reflective elements are sufficient to provide an acceptable system sum-rate

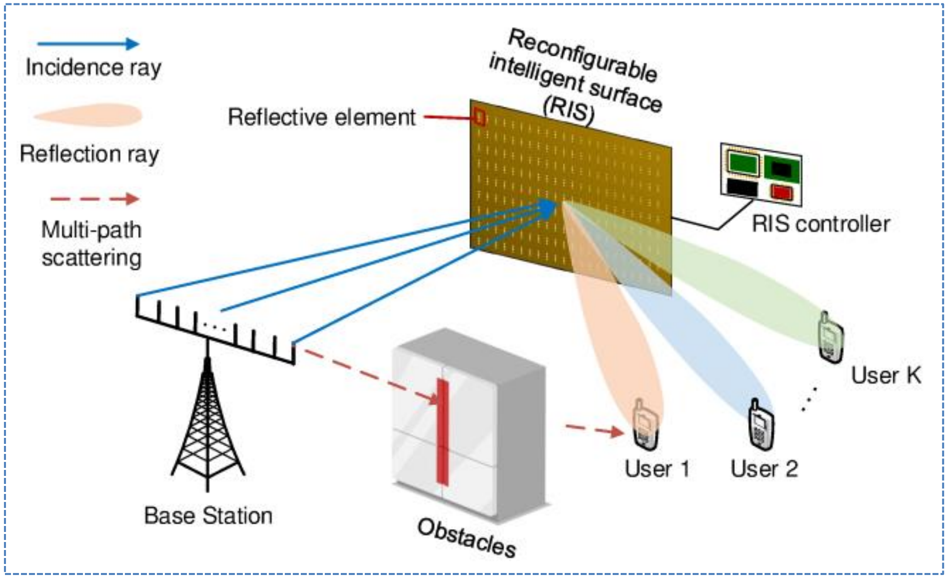
Contributions

- We provide an asymptotic analysis of the system capacity for the RIS-assisted downlink multi-user MISO communications with zero-forcing (ZF) precoding
- We discuss how the size of the RIS influences the data rate based on the derived achievable data rate expression.

System Model

System Description

- Single cell downlink network
- LoS between the BS and users is blocked
- RIS reflects signals from the BS to users



Data Rate Analysis

- When the number of elements is large, the channel response follows a Gaussian distribution (central limit theorem)
- With this assumption, the system capacity can be upper bounded by

Transmit power　　Number of RIS elements

$$C \leq \sum_{k} \log_2 \left(1 + \frac{P\Lambda_k}{K} \bar{\beta}^k \Gamma^2 M N \right)$$

Number of users　　Number of antennas

Analysis on Number of RIS Elements

- Minimize the number of elements with the constraint that the sum-rate can reach η of the system capacity bound

$$\min_{N} N, \quad s.t. \quad \epsilon \geq \eta.$$

Ratio of sum-rate to the system capacity bound (rate ratio)

- ϵ is hard to obtain since we do not have a closed-form expression of phase shifts: use the lower bound of ϵ instead
- Using Jensen's inequality, the lower bound of ϵ

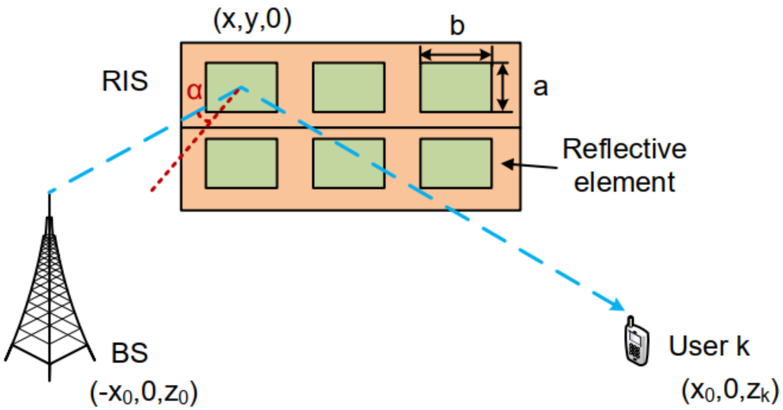
$$\hat{\epsilon} = \frac{\sum_k \log_2\left(1 + P\Lambda_k\Gamma^2\bar{\beta}^k N(\boxed{\mu} - 1)\right)}{\sum_k \log_2\left(1 + P\Lambda_k\Gamma^2\mu\frac{2Az_0^3\boxed{\lambda}^2}{5\pi^2(z_0+z_k)^5}\right)}$$

μ= # BS antennas/# users

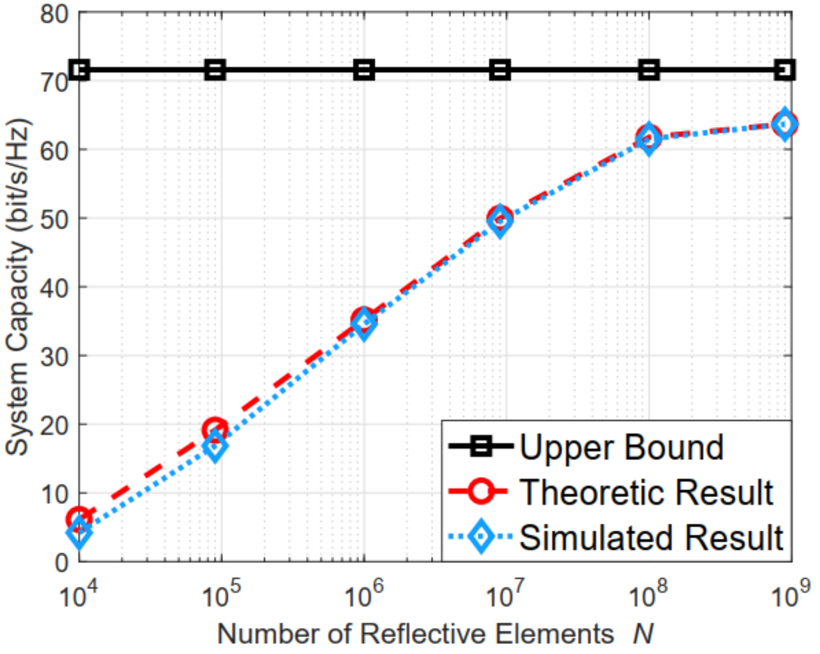
wavelength

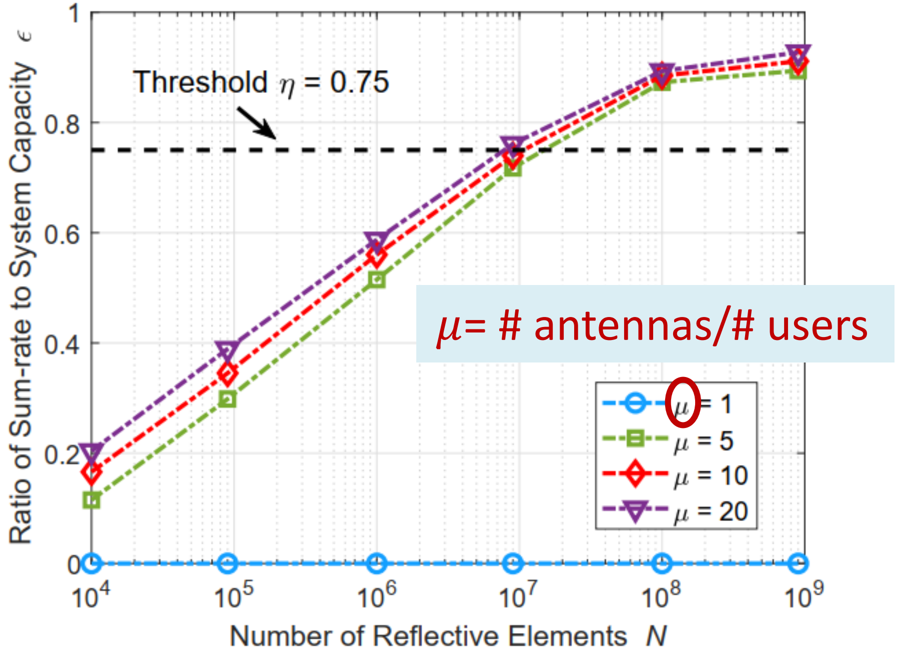
- The minimum number of elements

$$N \geq \left(\prod_k \frac{\left(P\Lambda_k\Gamma^2\mu\frac{2Az_0^3\lambda^2}{5\pi^2(z_0+z_k)^5}\right)^{\eta}}{P\Lambda_k\Gamma^2\bar{\beta}^k(\mu-1)}\right)^{1/K}$$



Simulation Results





μ= # antennas/# users

- The data rate per user will increase first and then become saturated
- The size of the RIS can be reduced with more antennas at the BS.
- It requires the number of reflective elements 8×10^6 to achieve 75% of the system capacity with μ = 20. (Side length of the RIS should be ~10m)

Case Study III: Orientation and Localization

Reconfigurable Intelligent Surface (RIS) Assisted Wireless Coverage Extension:

RIS Orientation and Location Optimization

S. Zeng, et al, “Reconfigurable Intelligent Surface (RIS) Assisted Wireless Coverage Extension: RIS Orientation and Location Optimization,” IEEE Communications Letters, vol. 25, no. 1, pp. 269-273, Jan. 2021.

Motivation and Contributions

Problems

- RIS deployment has an influence on the cell coverage
- However, existing works only utilized the RIS for coverage extension given the RIS location, but how to deploy the RIS to maximize the cell coverage has not been studied.

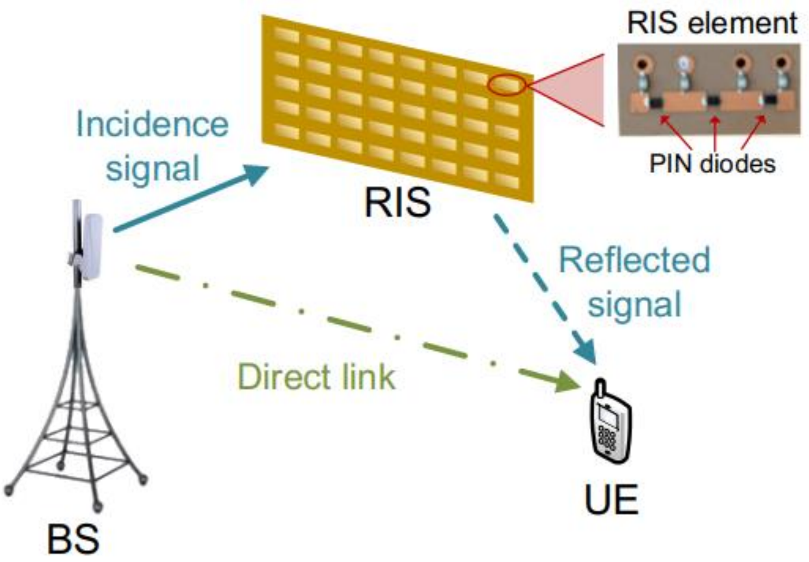
Contributions

- We provide an analysis on the cell coverage of an RIS-assisted downlink cellular network
- The cell coverage is maximized by optimizing the RIS orientation and the horizontal distance between the RIS and the BS.

System Model

Scenario Description

- Single-cell downlink
- One BS, one UE, and one RIS
- Direct link and reflected links
- Small scale fading of channels is averaged



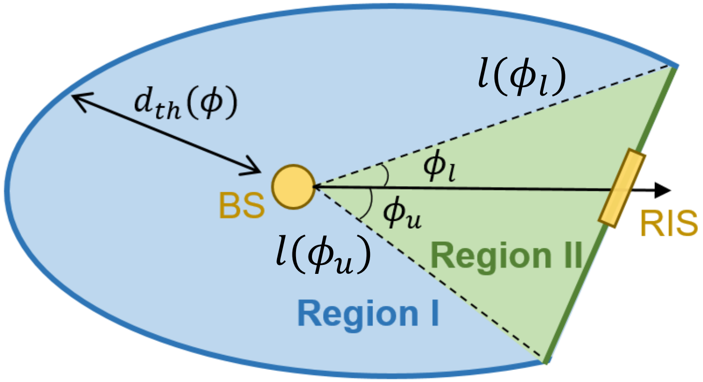
Cell Coverage

- Cell coverage is an area where the received SNR is larger than a threshold
- It can be divided into two regions

coverage in direction ϕ

length of the boundary

$$S = \underbrace{\int_{\phi_l}^{\phi_u} \frac{1}{2} d_{th}^2(\phi) d\phi}_{\text{Region I}} + \underbrace{\frac{1}{2}\sin(\phi_l - \phi_u) l(\phi_l) l(\phi_u)}_{\text{Region II}}$$

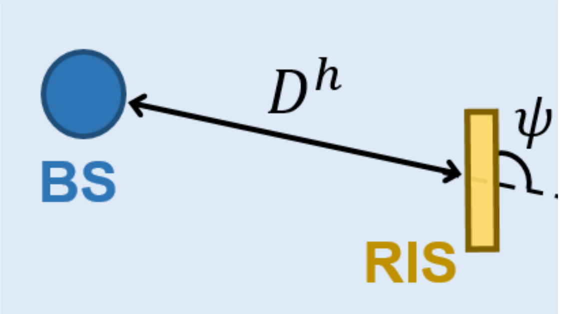


RIS Placement Optimization

$$\max_{\underline{D^h},\underline{\psi}} S = \int_{\phi_l}^{\phi_u} \frac{1}{2} d_{th}^2(\phi) d\phi + \frac{1}{2} \sin(\phi_l - \phi_u) l(\phi_l) l(\phi_u).$$

RIS orientation

Horizontal distance



RIS Orientation Optimization

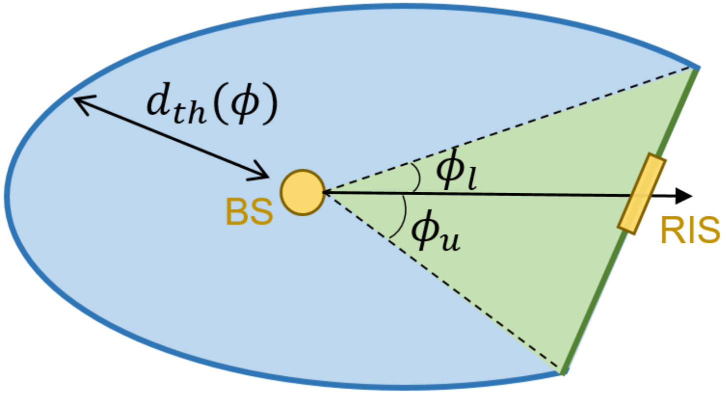
- For any horizontal distance, optimal RIS orientation: $\psi = \frac{\pi}{2}$

Horizontal Distance Optimization

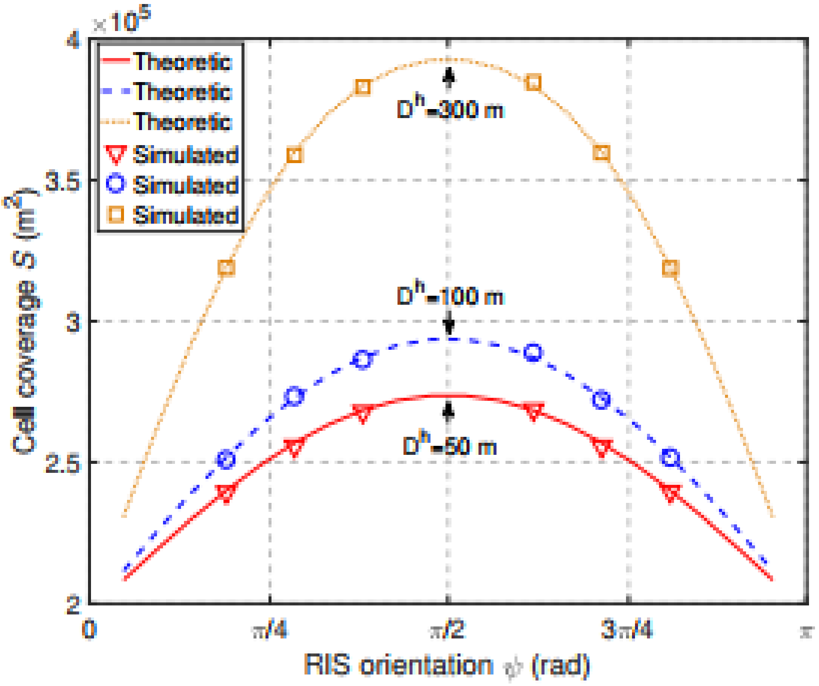
- $\phi_l, \phi_u, d_{th}(\phi)$ are coupled with D^h
- $\phi_l, \phi_u, d_{th}(\phi)$ have no closed form results
- Discretize into K parts

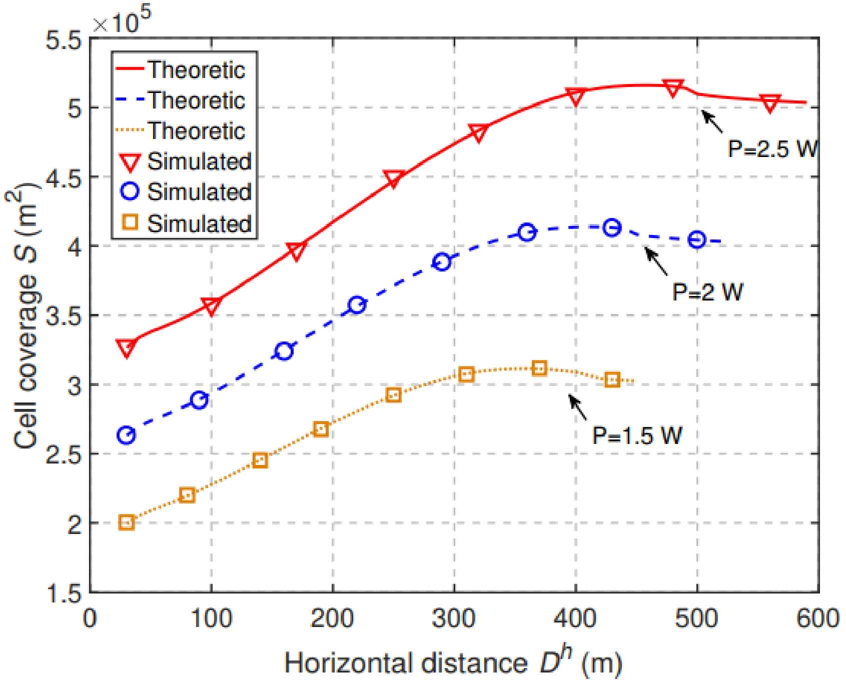
$$\int_{\phi_l}^{\phi_u} \frac{1}{2} d_{th}^2(\phi) d\phi \approx \sum_{i=0}^{K-1} \frac{1}{2} d_{th}^2(\phi_l + i\Delta)\Delta,$$

- Solved by interior point method



Simulation Results





- Simulation results are consistent with theoretical analysis
- The optimal RIS orientation is $\frac{\pi}{2}$
- The RIS should be placed at a moderate distance from the BS to improve the cell coverage

Case Study IV: RIS-aided Multi-User Communications

Hybrid Beamforming for RIS based Multi-User Communications:

Achievable Rates with Limited Discrete Phase Shifts

B. Di, et al, “Hybrid Beamforming for Reconfigurable Intelligent Surface based Multi-user Communications: Achievable Rates with Limited Discrete Phase Shifts,” IEEE Journal of Selected Areas in Communications, **vol. 38, no. 8, pp. 1809-1822, Aug. 2020**.

Motivation

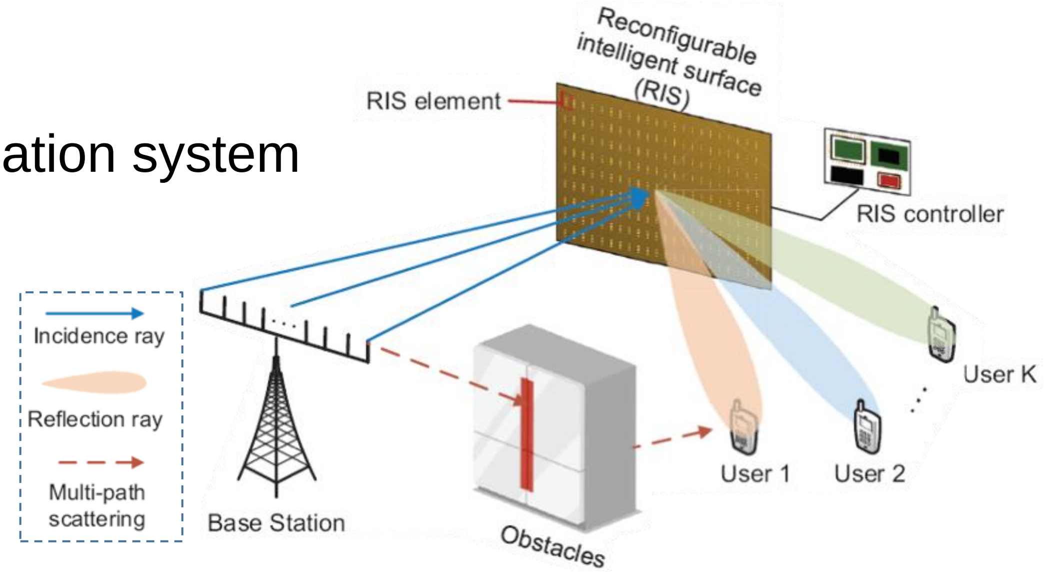
Problems

- RIS configuration:
    - Multi-user case: Inter-user interference exists
    - RIS elements has limited discrete phase shifts
- How to perform the beamforming to maximize the sum rate?

Challenges

- The channel propagation and the RIS configuration are coupled.
- Discrete phase shifts render the sum rate maximization to be a NP-hard mixed integer programming problem.

System Model

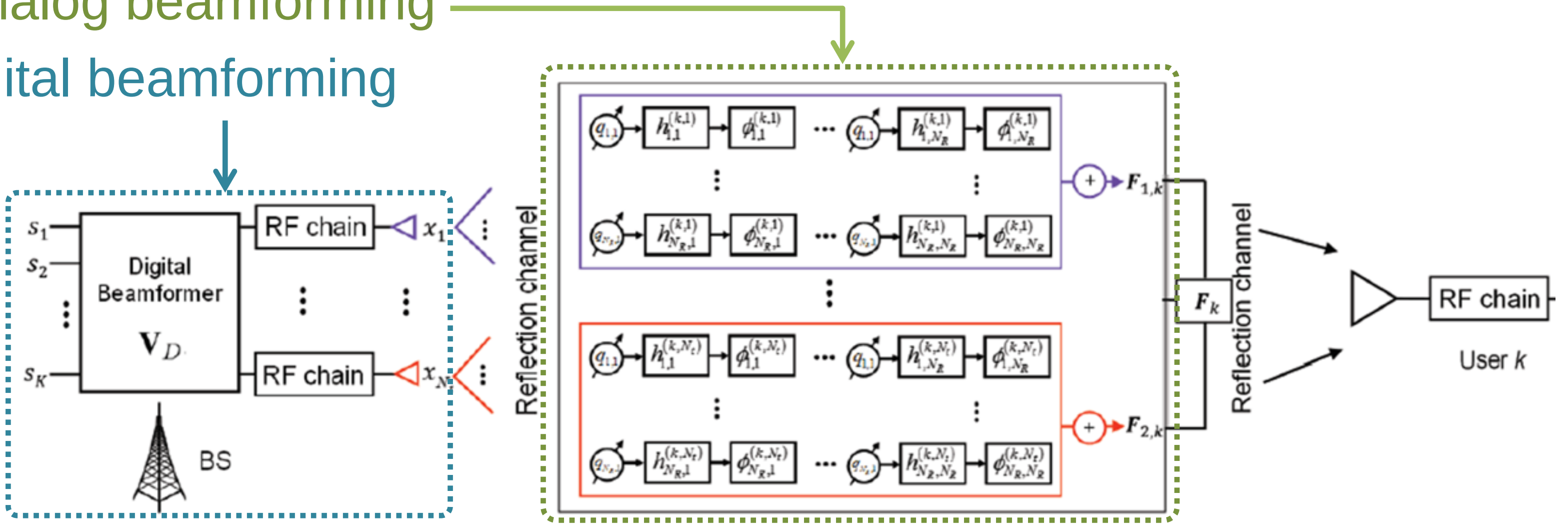


System Model

- Downlink multi-user communication system
- N_t-antennas BS
- K single-antenna users
- $N_R \times N_R$ RIS elements
  - b-bit quantization

Hybrid beamforming

- RIS → analog beamforming
- BS → digital beamforming



Problem Formulation

Available Rate of User K

$$R_k = \log_2\left(1+\frac{\left|\mathbf{F}_k^H\mathbf{V}_{D,k}\right|^2}{\sum\limits_{k'\neq k}\left|\mathbf{F}_k^H\mathbf{V}_{D,k'}\right|^2+\sigma^2}\right)$$

Channel coeff.

$$(\boldsymbol{F}_k)_n = Tr\left(\phi^{(k)}\boldsymbol{Q}^T\boldsymbol{H}^{(k,n)}\right)$$

Analog beamforming
(phase shifts)

Digital beamforming

Sum Rate Maximization Problem

$$\underset{\mathbf{V}_D,\{q_{l_1,l_2}\}}{\text{maximize}}\quad \sum_{1\leq k\leq K} R_k$$

$$\text{subject to}\quad \mathrm{Tr}\left(\mathbf{V}_D^H\mathbf{V}_D\right)\leq P_T,$$

Phase shift constraint

$$q_{l_1,l_2} = \frac{j+e^{j\theta_{l_1,l_2}}}{2},0$$

Quantization constraint

$$\theta_{l_1,l_2} = \frac{m_{l_1,l_2}\pi}{2^{b-1}},$$

decouple

Digital Beamforming Opt.

$$\underset{\mathbf{V}_D}{\text{maximize}}\quad \sum_{1\leq k\leq K} R_k,$$

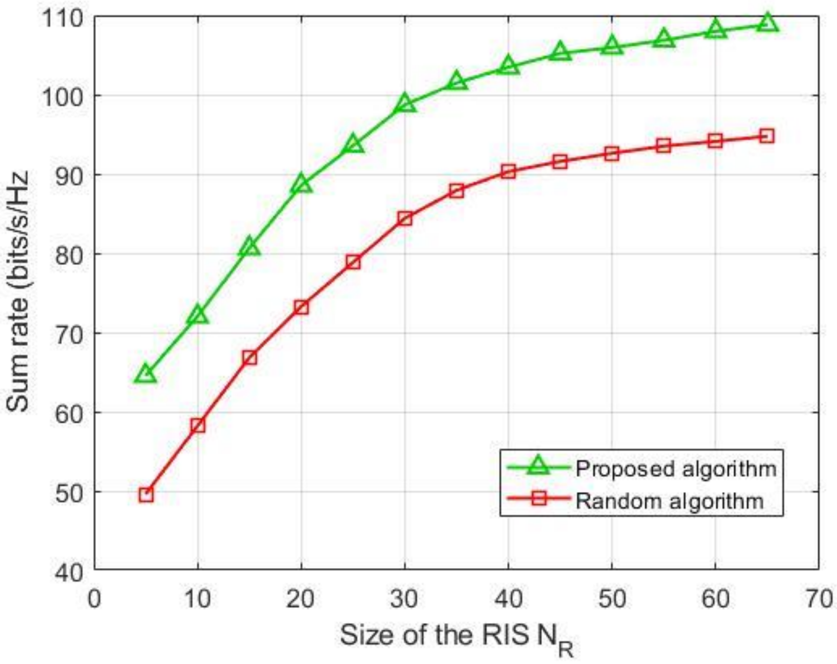
$$\text{subject to}\ \mathrm{Tr}\left(\mathbf{V}_D^H\mathbf{V}_D\right)\leq P_T.$$

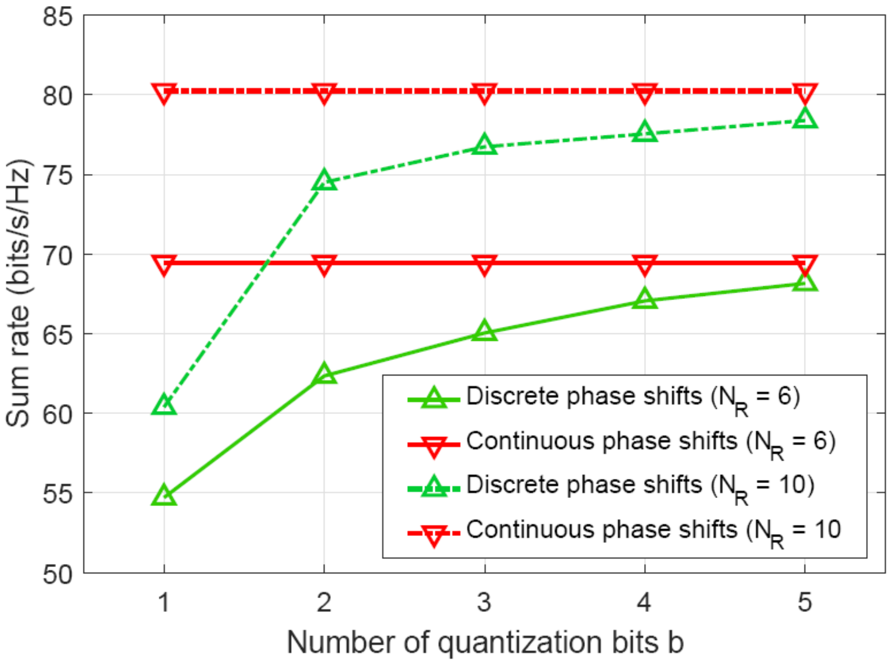
$$\underset{\{\theta_{l_1,l_2}\}}{\text{maximize}}\quad \sum_{1\leq k\leq K} R_k,$$

$$\text{subject to}\ \theta_{l_1,l_2} = \frac{m_{l_1,l_2}\pi}{2^{b-1}}$$

Analog Beamforming Opt.

Simulation Results





- The sum rate grows rapidly with a small size of RIS and gradually flattens as the size of RIS continues to increase.

- As the number of quantization bits increases, the sum rate obtained by our proposed algorithm approaches that in the continuous case.

Case Study V: Intelligent Omni-Surface

Intelligent Omni-Surface:

Ubiquitous Wireless Transmission by Reflective-Transmissive Metasurfaces

① S. Zhang et al, “Intelligent Omni-Surface: Ubiquitous Wireless Transmission by Reflective-Transmissive Metasurfaces,” IEEE Transactions on Wireless Communications, submitted.

② S. Zhang, H. Zhang, B. Di, Y. Tan, Z. Han, and L. Song, “Reflective-Transmissive Metasurface Aided Communications for Full-dimensional Coverage Extension,” IEEE Trans. Veh. Technol., vol. 69, no. 11, pp. 13905-13909, Nov. 2020.

Motivations and Contributions

Motivations

- Reflective RIS only serves users on one side, and shields the signals to the users on the other side
- We propose an intelligent omni-surface (IOS)-assisted downlink communication system, where the IOS transmits and reflects signals to the users on both sides simultaneously

Challenge

- How to control phase shifts of the IOS to serve users on two sides

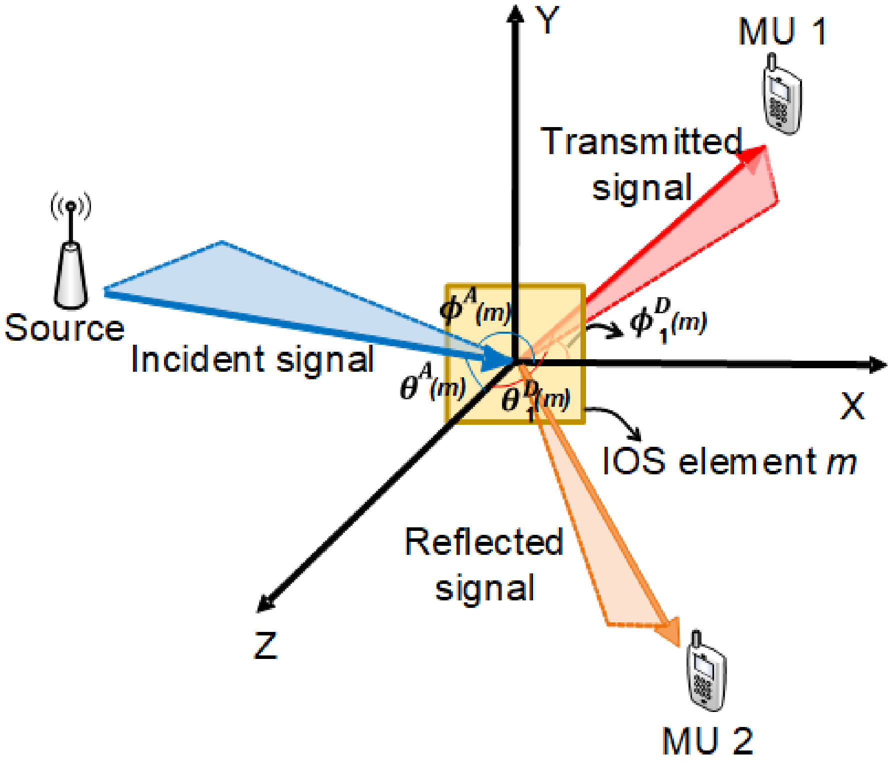
Contributions

- We design the BS digital beamforming and IOS beamforming jointly to maximize the sum-rate of the system.
- We study the relation between the optimal power ratio of the reflected and transmitted signals and the user distribution.

Signal Reflection-Transmission Model

Model of a reflective-transmissive RIS element

- Transmitted signal: $y = \sqrt{\frac{\varepsilon}{1+\varepsilon}} \Gamma e^{j\theta} x$
- Reflected signal: $y = \sqrt{\frac{1}{1+\varepsilon}} \Gamma e^{j\theta} x$
- ε: Reflected-transmitted power ratio
  - $\varepsilon = 0$: Fully reflected
  - $\varepsilon \to \infty$: Fully transmitted
- An element reflects and transmits signal simultaneously
- Reflective and transmissive signals through the same element have the same phase shift, but different amplitudes



System Model and Problem Formulation

System Model

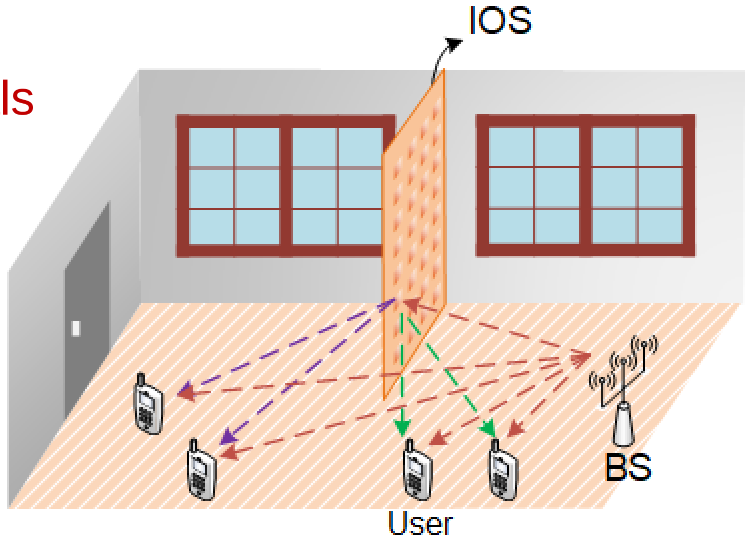
- IOS: *M* reflective-transmissive elements
- Downlink communication system
- K -antennas BS
- N single-antenna users distributed on two sides of the IOS
- Power radiation patterns of the IOS reflected and transmitted signals:

$$K_i^D(m) = \begin{cases} \frac{1}{1+\epsilon} |\cos^3 \theta_i^D(m)|, \ \theta_i^D(m) \in (0, \pi/2), & \longrightarrow \text{Reflected signals} \\ \frac{\epsilon}{1+\underline{\epsilon}} |\cos^3 (\theta_i^D(m))|, \ \theta_i^D(m) \in (\pi/2, \pi), & \longrightarrow \text{Transmitted signals} \end{cases}$$

Power ratio of reflected and transmitted signals

Problem Formulation

- Joint BS digital beamforming and IOS beamforming design
- Maximize sum-rate of all the users



Problem Decomposition and Analysis

Joint BS digital beamforming and IOS beamforming

- NP-hard problem, decouple into two sub-problems

Digital Beamforming Optimization at the BS

$$\max_{\mathbf{V}_D} \sum_{i=1}^{N} R_i,$$

$$s.t. \boxed{\mathrm{Tr}\left(\mathbf{V}_D\mathbf{V}_D^H\right) \leq P_B}$$

BS transmission power constraint

Analog Beamforming Optimization at the IOS

$$\max_{s} \sum_{i=1}^{N} R_i,$$

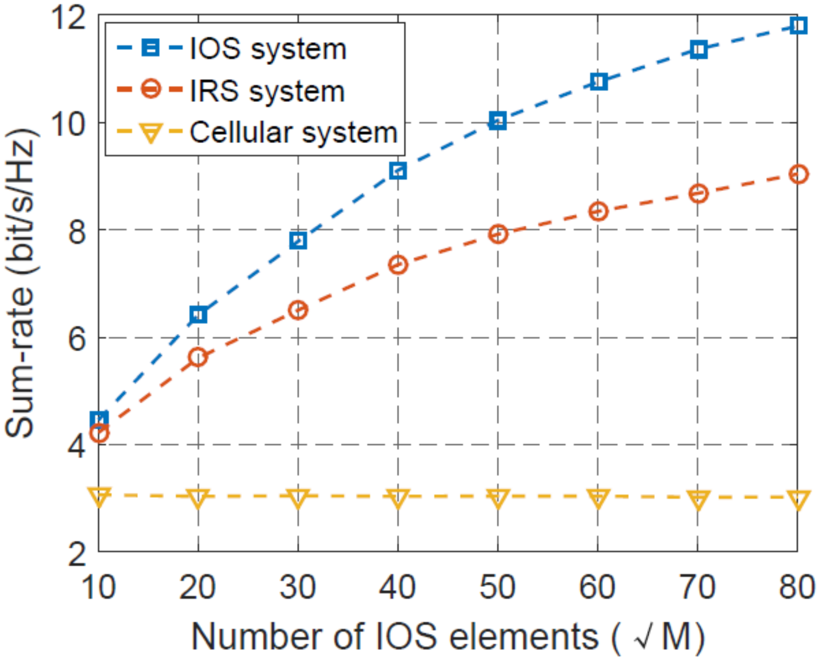
$$s.t. \boxed{s_m \in \mathcal{S}_a, m = 1, 2, \ldots, M.}$$

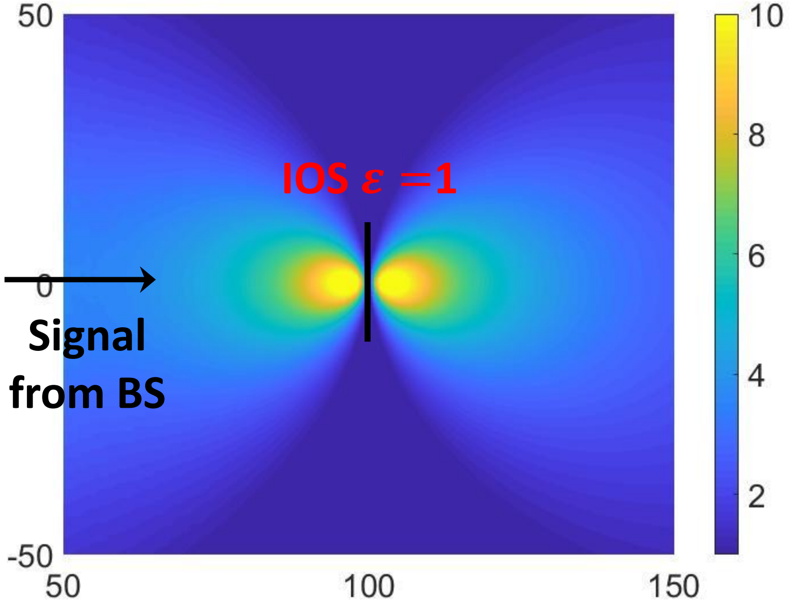
Available phase shifts of IOS elements

Analysis on reflected and transmitted signals

- The optimal power ratio of reflected and transmitted signals is positively correlated with the number of users on the two sides of the IOS
- To maximize the sum-rate, larger proportion of the power should be allocated to the users with weaker direct links

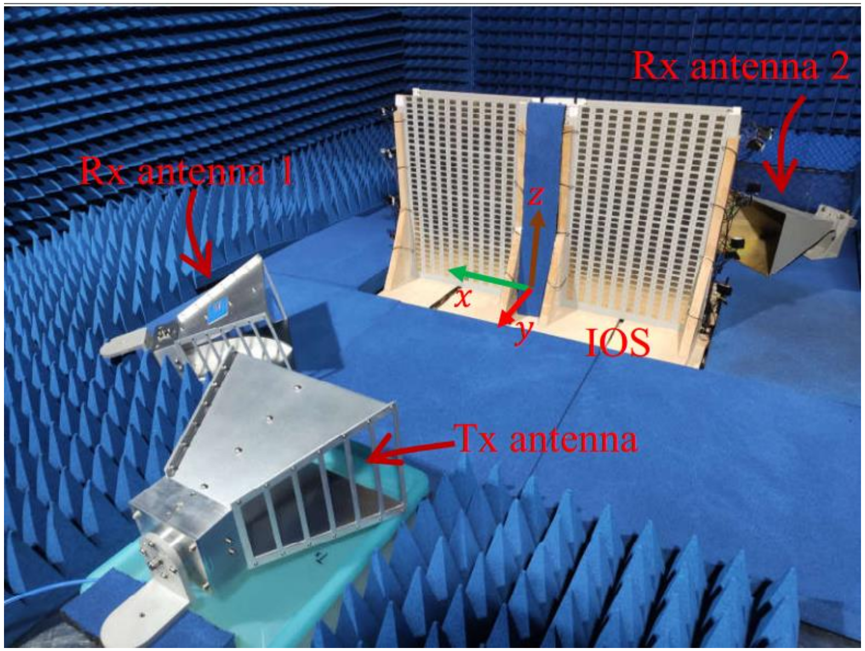
Simulation Results



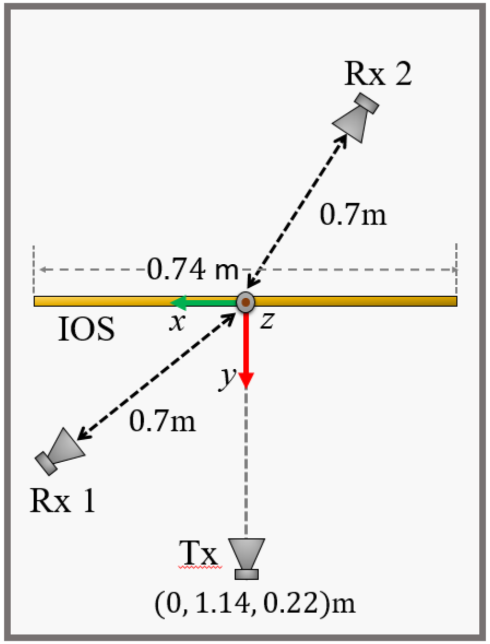


- IOS significantly improves the average sum-rate when compared to a conventional cellular, and can provide 30% higher sum-rate improvement than the reflective RIS
- IOS can efficiently improve the downlink data rate on both sides of it

Prototype of Intelligent Omni-Surface



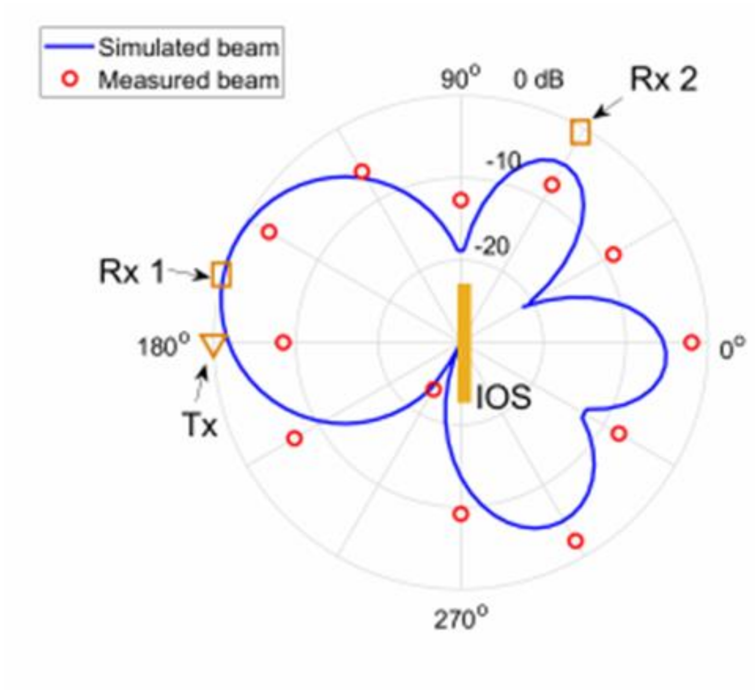
Full View



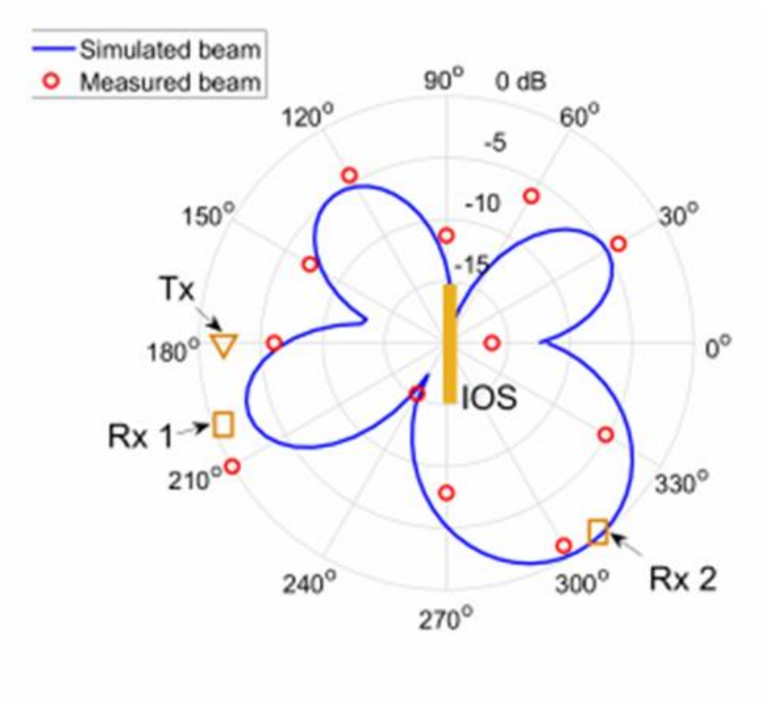
Top View

- Two Rxs: one on each side of the IOS
- Tx perpendicular to the IOS to reduce line-of-sight signals
- Implementation of IOS: 16 groups, 5*8 elements in one group, and states of elements in one group are the same

Initial Experimental Results



State 1



State 2

- The radiation pattern shows that the IOS can cover UEs on both sides
- By configuring the IOS state, the IOS can generate different beams

Potential Directions

RIS-based Multi-cell / Multi-user Coordination

- RIS-based D2D communications
- RIS-based NOMA
- RIS-based cell-free MIMO

Channel Estimation and Modelling

- Semi-passive RIS channel estimation
- Passive RIS channel estimation

Other issues

- Joint coding and transmission
- Physical-layer security
- Energy efficiency

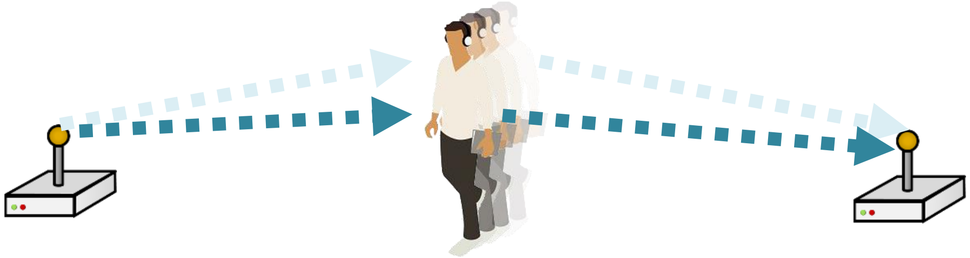
Table of Contents

Background

- **RF sensing**
  - Living environment is covered seamlessly by wireless signals
  - Ubiquitous signals provide the foundation for RF sensing

Visualization of cellular signals

- **Principles:**
  - Sensing targets between a pair of RF Tx and Rx impact the RF channel .
  - The Rx can recognize different sensing targets by getting different received signals.



Received signals change due to change of target

Applications

Security

Theft Detection

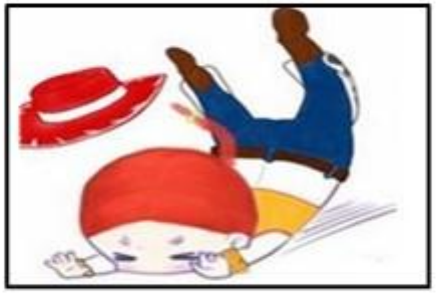
Theft detection

Smart Space

Interaction

Emergency Alarm

Safety



Fall Detection

Elderly Care

- **Advantages:**
  - No needs for the contact or line-of-sight view of the sensing targets

Techniques Review

- **Active Methods**
  - WiFi Sensing:
    - Utilize the impact of the targets on WiFi signals
    - Various metrics: signal strength, phase, doppler and so on
  - mmWave Radar:
    - Utilize the directional beams in mmWave communications
    - Receivers can detect reflected signals from targets
- **Limitations:** sensing accuracy is limited by channel conditions

↓ Solution

- **Passive Method:** RIS-aided RF sensing

Goals and Challenges

Goals

- Implement practical RIS-aided RF sensing system for human and object localization and recognition
- Achieve high sensing accuracy

Challenges

- Design practical sensing protocols to coordinate the RIS and the RF transceiver.
- Search the optimal phase shift selection for the RIS elements in a large feasible region.
- Propose efficient algorithms to obtain semantic meaning and location information of human and objects from received signals.

Case Study VI: RIS aided Posture Recognition

RIS-based RF Sensing:

Design, Optimization, and Implementation

J. Hu, et al, “Reconfigurable Intelligent Surfaces based RF Sensing: Design, Optimization, and Implementation,” IEEE Journal of Selected Areas in Communications, vol. 38, no. 11, pp. 2700-2716, Nov. 2020.

Motivation

RIS-based RF sensing system

- RIS can control the wireless environment, which can provide favorable wireless environment for RF sensing.
- Application in human posture recognition:
  - Recognize different human postures automatically

Challenges

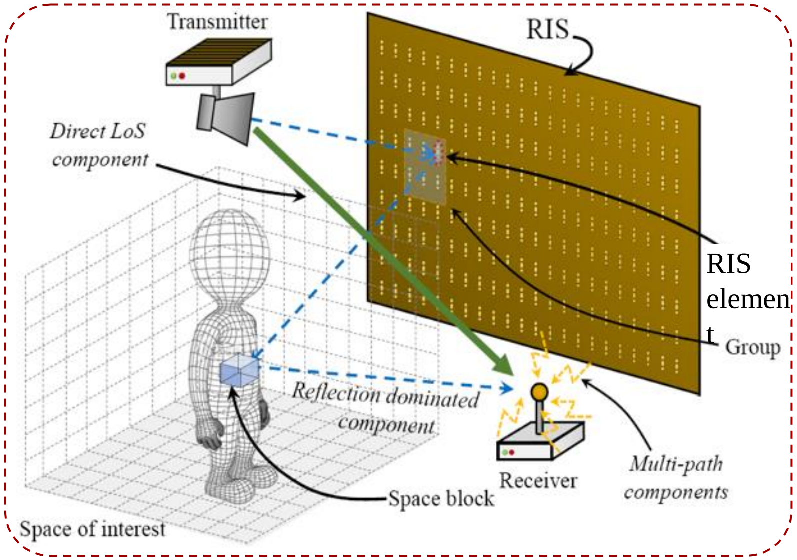
- RIS configuration design – *How RIS controls the wireless environment*
  - The discrete phase shifts of a massive number of RIS elements need to be determined.
- Decision function design – *How Rx judges human posture*
  - The integration of the RIS makes the relationship between Rx signals and human posture more complicated.
- Moreover, RIS configuration and decision function are coupled.

Model Description

System Structure

- Transmitter: A directional antenna which is pointed towards the RIS
- Receiver: An omni-directional vertical antenna below the RIS
- Human： Space reflection vector carries the information of postures.
- RIS: RIS elements in the same group are in the same state.

Channel Model



- Multi-path component:
  - Environment scattering
- LoS component:
  - Transmitter → Receiver
- Reflection dominated components
  - Transmitter → RIS → Human → Receiver

Periodic Configuring Protocol

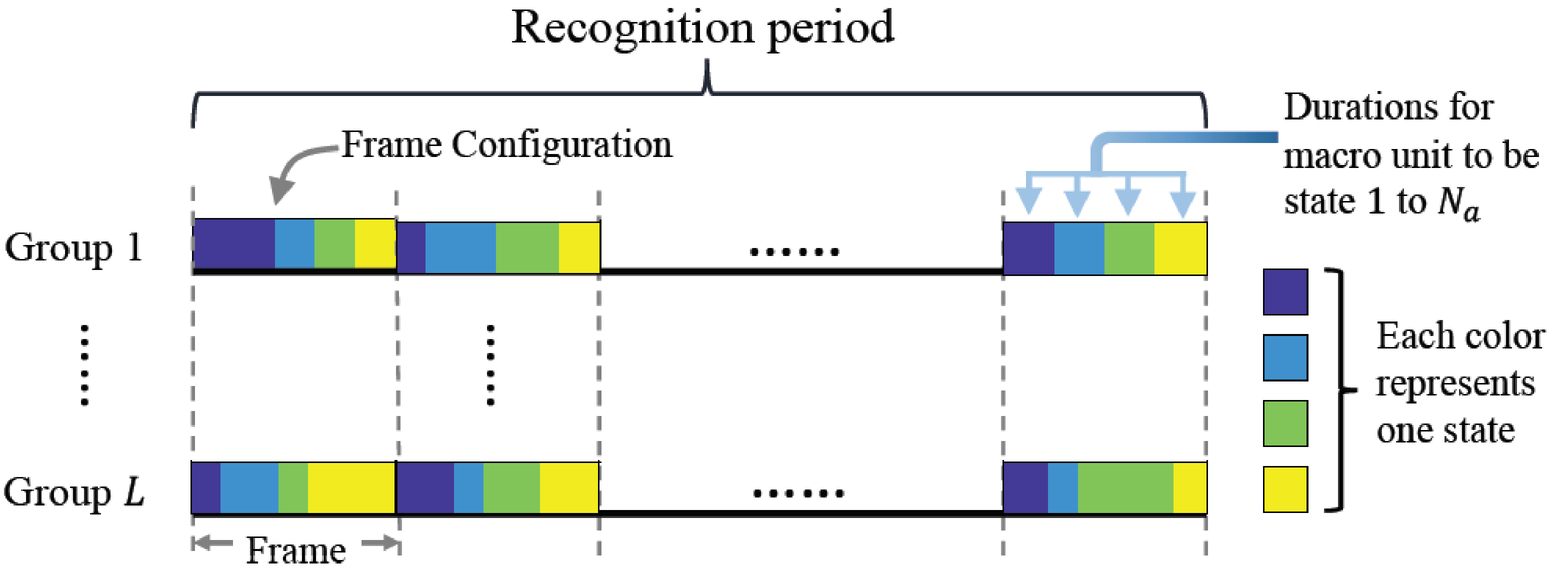
Recognition Period:

- Contains K *frames*, during which the human posture is fixed
- Received signals during a recognition period are used for recognition

Frame Configuration:

Different *states* correspond to different *phase shifts*

- Each group of RIS elements sequentially changes from State 1 to N_a.
- Constituted by the durations that each group stays in the N_a states



Problem Formulation

Decision Function: The receiver uses the decision function to generate the probabilities for deciding on different human postures.

Optimization Problem: Minimize the false recognition cost

$$\text{(P1)} \quad \min_{\boldsymbol{T},\boldsymbol{\mathcal{L}}} C_{FR}(\boldsymbol{T},\boldsymbol{\mathcal{L}}) = \sum_{i,i'} \Pr(\text{pos}_i) \cdot cost(i,i') \cdot \mathbb{E}_{\boldsymbol{y}}[\Pr(\boldsymbol{y}|\text{pos}_i) \cdot \mathcal{L}_{i'}(\boldsymbol{y})]$$

Optimization Variables

$\boldsymbol{T}$: Frame configurations in a recognition period

$\boldsymbol{\mathcal{L}}$: Decision function

Probability of Posture i to appear

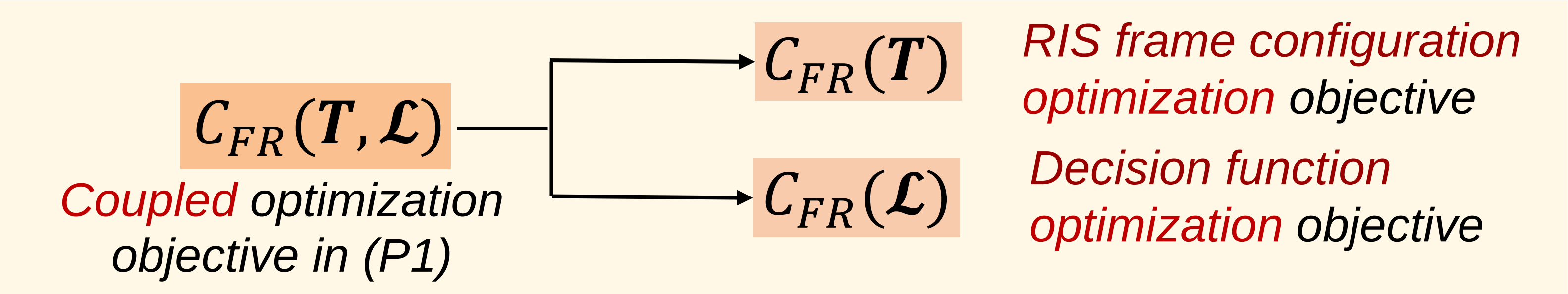
Cost for recognizing Posture i as i'

$\boldsymbol{y}$: Measured signals in a period

$\mathcal{L}_{i'}(\boldsymbol{y})$: Probability for deciding on Posture i' given $\boldsymbol{y}$

Problem Decomposition:

- Decomposing (P1) into the frame configuration optimization and the decision function optimization.



$C_{FR}(\boldsymbol{T},\boldsymbol{\mathcal{L}})$

Coupled optimization objective in (P1)

$C_{FR}(\boldsymbol{T})$

RIS frame configuration optimization objective

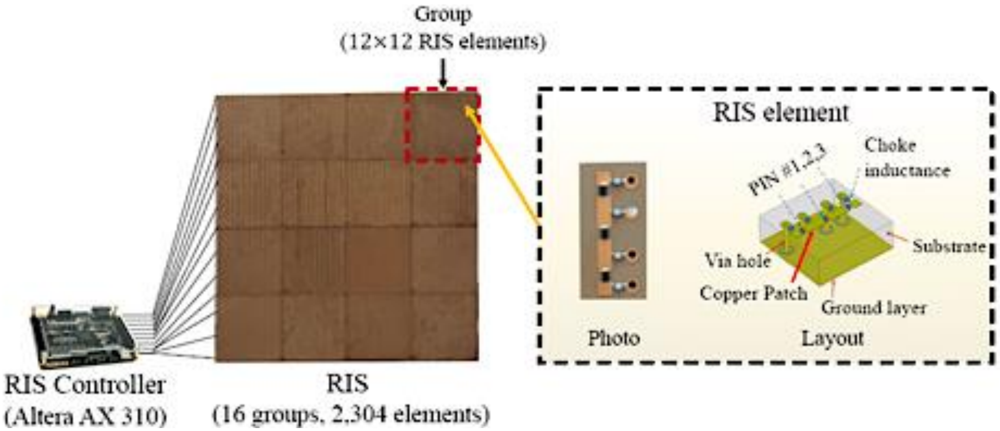
$C_{FR}(\boldsymbol{\mathcal{L}})$

Decision function optimization objective

Implementation

RIS & RIS Control Circuit

- **Size of RIS:** 69 $\times$ 69 $\times$ 0.52 cm^3
- **Dielectric substrate:** Rogers 3010 (dielectric constant:ε =10.2)
- **PIN diodes:** BAR 65-02L × 3
- **Total number of possible phase shifts**: 8
  - Four of them are used with phase shifts ($\frac{\pi}{8}, \frac{3\pi}{8}, \frac{5\pi}{8}, \frac{7\pi}{8}$)
- **RIS controller:** FPGA ALTERA-AX301



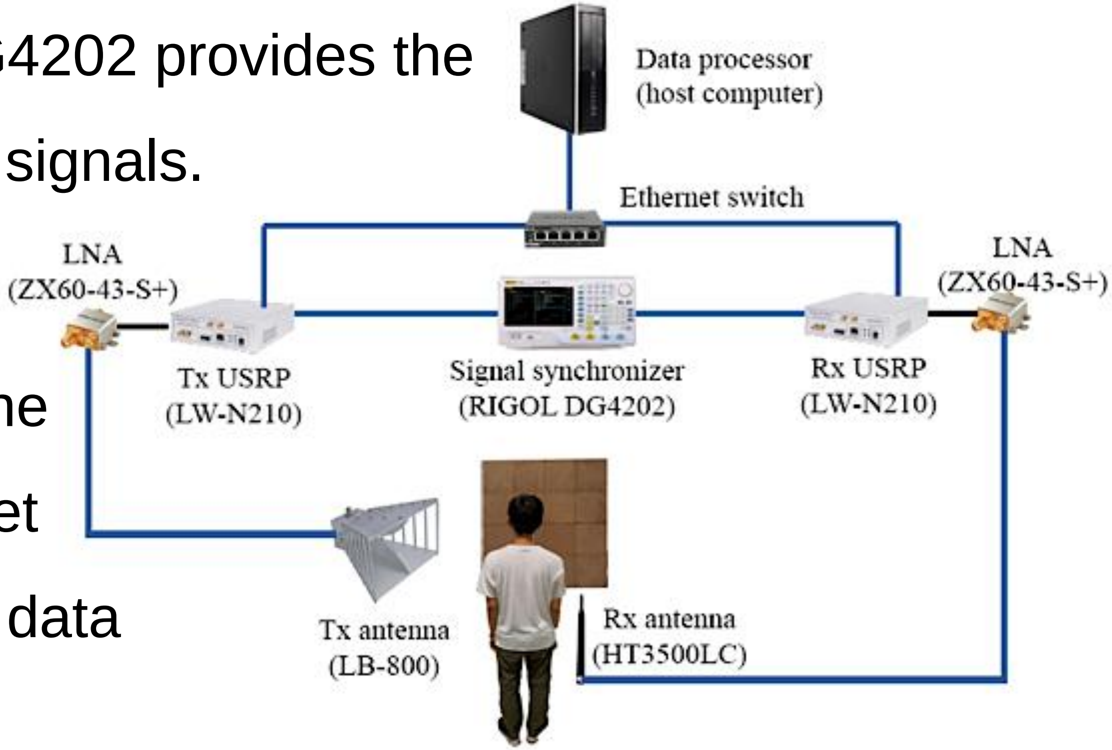
Implementation

RF Circuit

- **Baseband Processor:** USRPs LW-N210
- **RF Board:** SBX-120W (0-6GHz, Max Power = 100mW)
- **Amplifier**: ZX60-43-S+ (Gain around 17dB)
- **Synchronizer**: RIGOL DG4202 provides the pps and clock signals.

Date Processor

- Host computer connects the Tx/Rx USRPs with Ethernet to send/receive baseband data



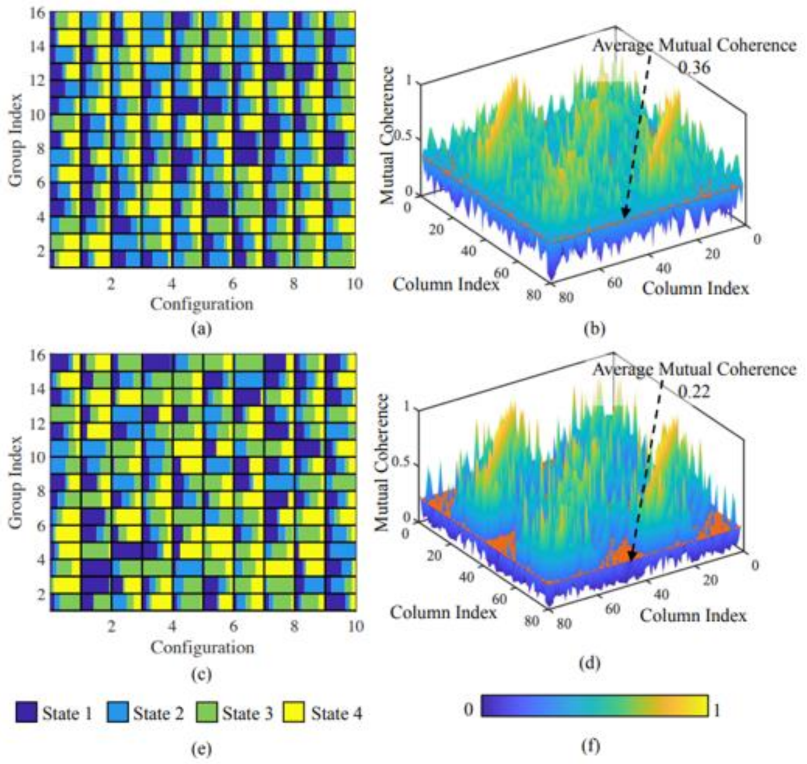
Experimental Results

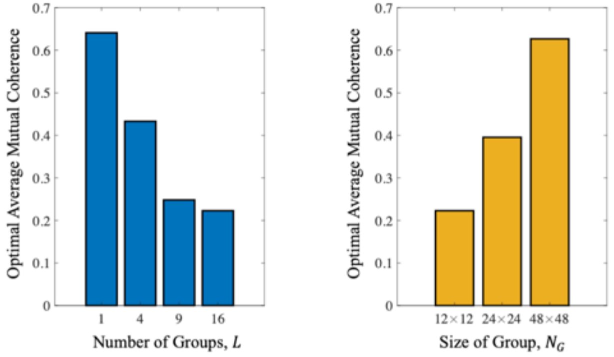
Effectiveness:

- The average mutual coherence of the measurement matrix is reduced, which can improve sensing accuracy.

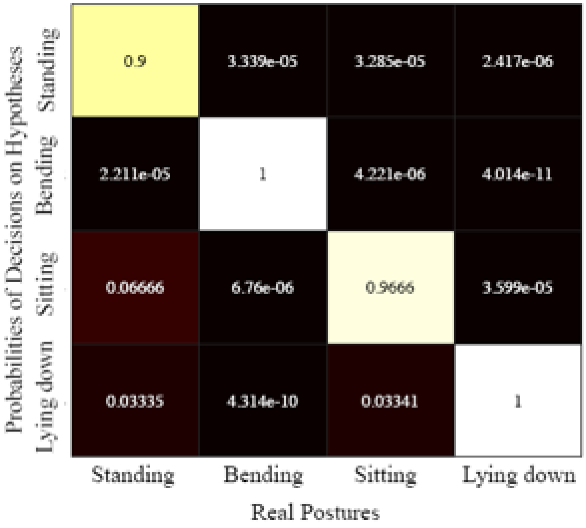
Insights:

- The optimized average mutual coherence decreases with the number of groups that the RIS contains, i.e., the size of the RIS.
- The optimal average mutual coherence increases with the size of groups.





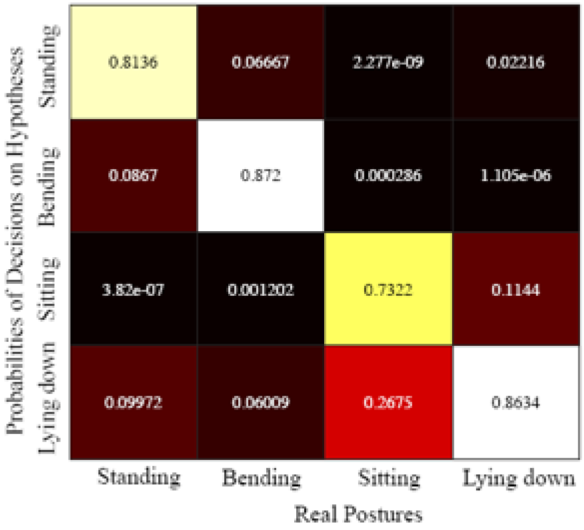
Experimental Results



	Standing	Bending	Sitting	Lying down
Standing	0.9	3.339e-05	3.285e-05	2.417e-06
Bending	2.211e-05	1	4.221e-06	4.014e-11
Sitting	0.06666	6.76e-06	0.9666	3.599e-05
Lying down	0.03335	4.314e-10	0.03341	1

(a)

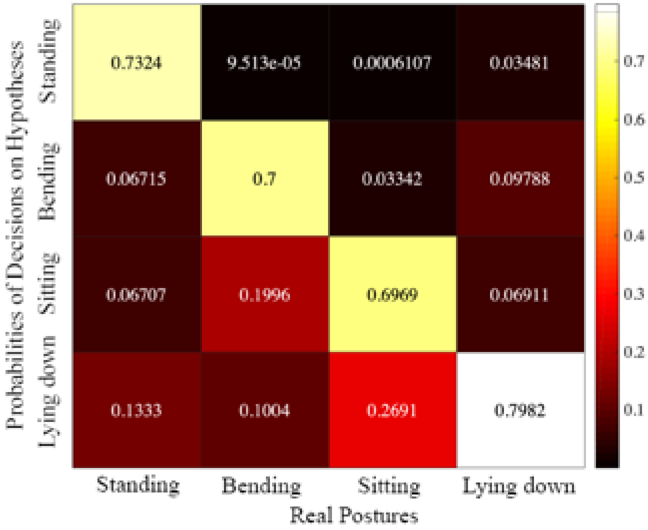
Proposed method



	Standing	Bending	Sitting	Lying down
Standing	0.8136	0.06667	2.277e-09	0.02216
Bending	0.0867	0.872	0.000286	1.105e-06
Sitting	3.82e-07	0.001202	0.7322	0.1144
Lying down	0.09972	0.06009	0.2675	0.8634

(b)

Random method



	Standing	Bending	Sitting	Lying down
Standing	0.7324	9.513e-05	0.0006107	0.03481
Bending	0.06715	0.7	0.03342	0.09788
Sitting	0.06707	0.1996	0.6969	0.06911
Lying down	0.1333	0.1004	0.2691	0.7982

(c)

Without RIS method

- Compared with traditional RF sensing systems, RIS increases the posture recognition accuracy with 23.5%.
- Compared with the system with random frame configurations, the system with optimized frame configurations achieves 14.6% higher recognition accuracy.

Case Study VII: RIS aided RF 3D Sensing

MetaSensing:

Intelligent Metasurface Assisted RF 3D Sensing by Deep Reinforcement Learning

J. Hu, et al, “MetaSensing: Intelligent Metasurface Assisted RF 3D Sensing by Deep Reinforcement Learning,” IEEE Journal of Selected Areas in Communications, under review.

Motivation

RF 3D sensing:

- From optical images, the complete information about 3D objects is hard to acquire due to the blocking of themselves.
- RF signals can detect these space of objects by reflection and scattering, which makes 3D sensing possible from RF signals

RIS-based 3D sensing

- The RIS controls RF signal beams by manipulating configuration
- Using controlled RF signal beams, the RIS can obtain more information about 3D objects in space and construct their shapes.

Challenges

- How to optimize the RIS's configuration to create favorable propagation channels for sensing
- How to obtain the mapping from RF signals to 3D shapes.

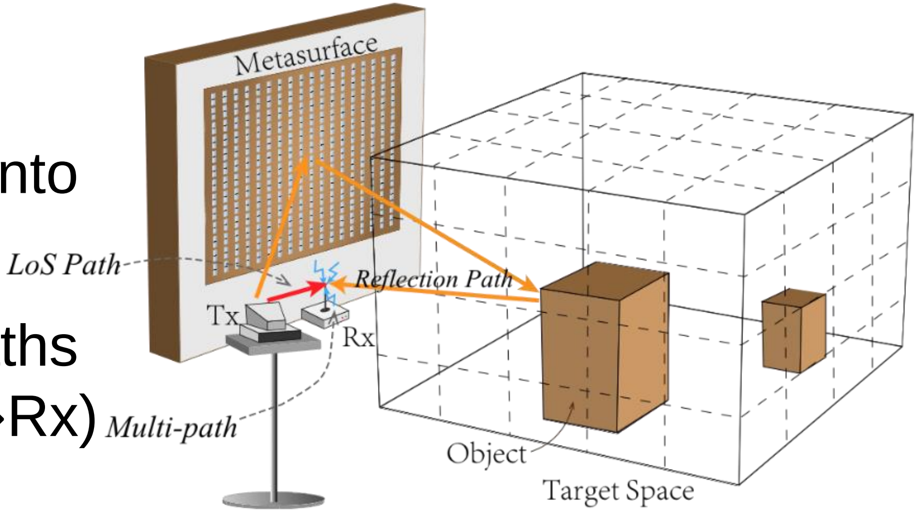
Model Description

System Description

- **Transmitter**: A directional antenna which is pointed towards the RIS
- **Receiver**: An omni-directional vertical antenna below the RIS
- **RIS:** Contains N meta-elements, each with N_S phase shifts
- **Sensing Target**: Existence of objects at M space grids

Channel Model

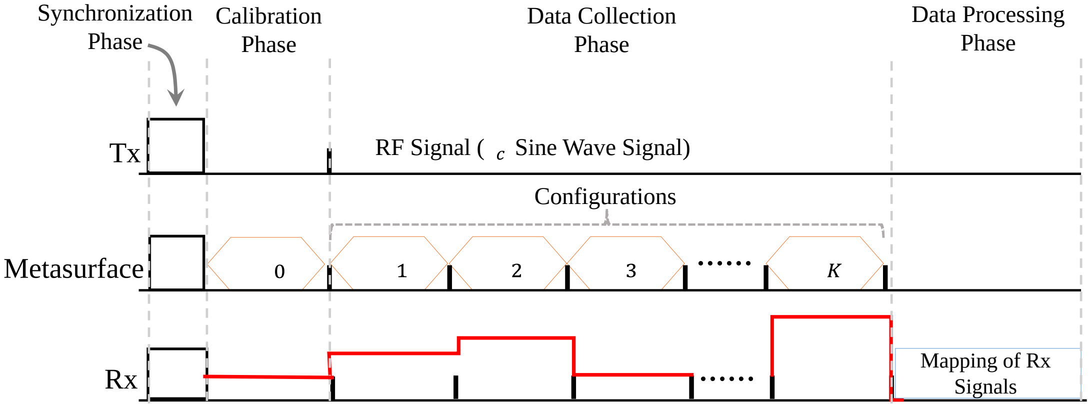
- The target space is discretized into M space grids.
- The total $N \times M$ reflection paths (Tx→ N RIS elements→ M grids→Rx) are summed at the Rx



Sensing Protocol

RF Sensing Protocol

- **Synchronization Phase:** synchronizes the Tx transmission, the RIS's configuration changes, and Rx reception
- **Calibration Phase:** the RIS is in $\boldsymbol{c}_0$ (no phase shifts incurred), and the received signal is used to subtract the environmental scattering.
- **Data Collection Phase:** RIS changes its configuration with equal time interval, and the Rx averages the received signals in each config.
- **Data Processing Phase:** The Rx use a decision function to determine the objects' existence at different space grids.



Problem Formulation

Decision Function: The Rx use the mapping function $\boldsymbol{f}^{\boldsymbol{w}}$ to estimate the probabilities for objects to be at M space grids, i.e., $\hat{\boldsymbol{p}} \in [0,1]^M$.

Optimization Problem: Minimize the *cross-entropy (CE) loss* given configuration matrix $\boldsymbol{C}$ and mapping function parameters $\boldsymbol{w}$

Entropy of Ground Truth
p_m: true probability of m-th grid being non-empty

Entropy of Estimation
$\hat{p}_m$: estimated probability of m-th grid being non-empty

$$(\mathrm{P1}): \min_{\boldsymbol{C},\boldsymbol{w}} \; -\mathbb{E}_{\boldsymbol{p}}\Big[\sum_{m=1}^{M} \boxed{p_m \cdot \ln(\hat{p}_m)} + \boxed{(1-p_m)\cdot \ln(1-\hat{p}_m)}\Big],$$

$$s.t. \; (\hat{p}_1, \dots, \hat{p}_M) = \boldsymbol{f}^{\boldsymbol{w}}(\tilde{\boldsymbol{y}}),$$

$$\tilde{\boldsymbol{y}} = \sqrt{P} \cdot x \cdot (\boldsymbol{C} - \boldsymbol{C}_0)\boldsymbol{A} + \tilde{\boldsymbol{\sigma}},$$

$$\begin{cases} \boldsymbol{C} = (\boldsymbol{c}_1^T, \dots, \boldsymbol{c}_K^T)^T, \\ \boldsymbol{c}_k = (\hat{\boldsymbol{o}}(c_{k,1}), \dots, \hat{\boldsymbol{o}}(c_{k,N})), \; \forall k \in [1, K], \\ c_{k,n} \in [1, N_S], \; \forall k \in [1, K], n \in [1, N]. \end{cases}$$

Constraints

(1) Estimation is obtained by mapping of received signals

(2) Rx signal is determined by RIS configuration $\boldsymbol{C}$

(3) Config. $\boldsymbol{C}$ consists of the phase shifts of the N RIS elements in K time intervals

Challenge :

- Optimization of config. $\boldsymbol{C}$ and mapping $\boldsymbol{f}^{\boldsymbol{w}}$ are highly coupled.

Algorithm Design

- Decompose (P1) into configuration optimization and mapping function optimization problems

Coupled optimization objective in (P1)

$CE(\boldsymbol{C}, \boldsymbol{f}^{\boldsymbol{w}})$

RIS configuration optimization (sP1)

$CE(\boldsymbol{C})|\boldsymbol{f}^{\boldsymbol{w}}$

Challenge: Configuration matrix $\boldsymbol{C}$ is an integer matrix and has a large number of elements.

Solution: Propose a deep reinforcement learning algorithm which can find the optimal policy for selecting $\boldsymbol{C}$.

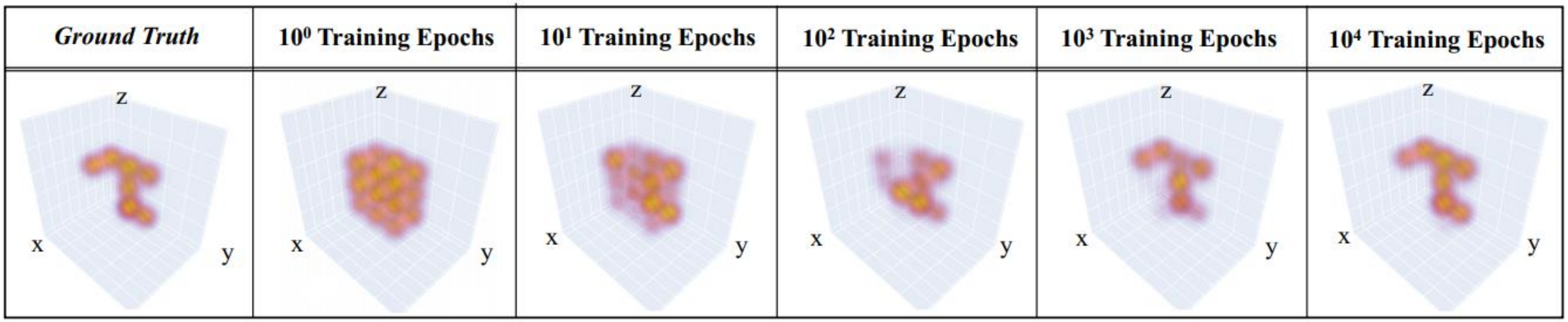
Mapping function optimization (sP2)

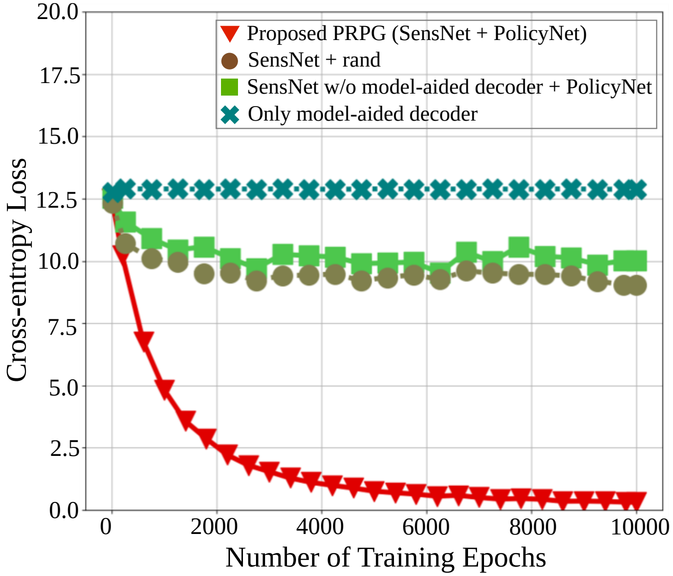
$CE(\boldsymbol{f}^{\boldsymbol{w}})|\boldsymbol{C}$

Challenge: Mapping function $\boldsymbol{f}^{\boldsymbol{w}}$ has unknown form and parameter $\boldsymbol{w}$.

Solution: Model $\boldsymbol{f}^{\boldsymbol{w}}$ by a neural network depicting an arbitrary function and propose a supervised learning algorithm to train $\boldsymbol{w}$.

Simulation Results





- Sensing results of a 3D object gets close quickly to the ground truth as the training proceeds
- The proposed algorithm converges with a high speed
- The proposed algorithm results in the lowest CE loss among all benchmark algorithms.

Case Study VIII: RIS aided Localization

Towards Ubiquitous Positioning by Leveraging RIS

① H. Zhang, et al, “Towards Ubiquitous Positioning by Leveraging Reconfigurable Intelligent Surface,” IEEE Commun. vol. 25, no. 1, pp. 284-288, Jan. 2021.

② H. Zhang, et al, “MetaRadar: Indoor Localization by Reconfigurable Metamaterials,” IEEE Trans. Mobile Comput., to appear. Arxiv: https://arxiv.org/abs/2008.02459.

Background

Radio Frequency (RF) based Positioning:

- Applications: Navigation, healthcare monitoring, indoor positioning
- Categories:
  - Received signal strength (RSS)
  - Channel state information (CSI)
  - Angle-of-arrival (AoA)
  - Time-of-arrival (ToA)

RSS based Positioning:

- Advantages: simplicity of measuring RSS and minimum hardware requirements
- Principle: users' locations are obtained by comparing the measured RSS and the stored RSS distribution in the indoor environment.

Motivation

Limitations of Traditional Methods

- The RSS distribution is passively measured and cannot be customized
- The localization performance degrades if RSS values are similar to each other in the RSS distribution

RIS aided Positioning:

- Users receive the signals from the AP and the RIS.
- RIS adjusts the RSS distribution by changing its configuration.

Challenges

- Localization protocol design: coordination among the RIS, AP and users.
- RIS configuration design
  - Large number of RIS configurations.
  - Complicated relation between the RIS configuration and the RSS distribution.

System Model

Positioning Scenario

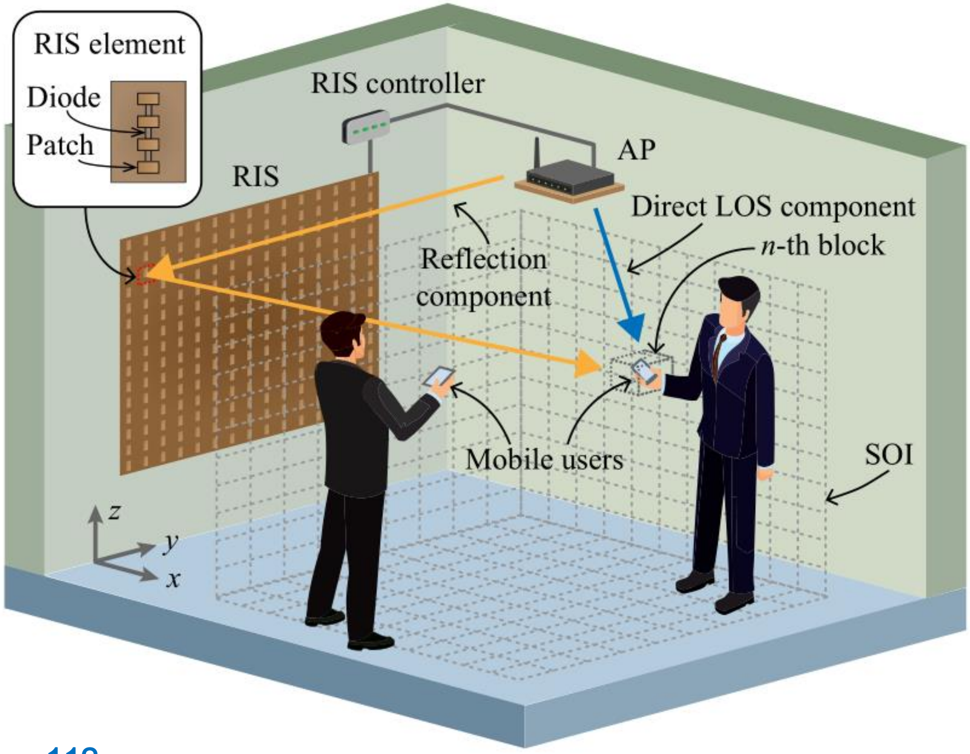
- AP: sends signals to the RIS and mobile users.
- RIS: reflects the signals from the AP to the users.
- Users: measure the RSS for positioning.
- Space of Interest (SOI): is discretized into *N* blocks to represent users' positions.

RIS Model

- *M* elements.
- Each element has *C* states with different reflection coefficients.

$$r_m(c_m) = \underbrace{r(c_m)}_{\text{Amplitude}} e^{\underbrace{-jc_m\Delta\theta}_{\text{Phase shift}}}$$

- Configuration $\boldsymbol{c}$: the vector of all the elements' states



System Model

RSS Model

- Direct LOS channel h_{lo}: AP → User at the n-th block
- Reflection channel $h_{m,n}(c_m)$: AP → element m → User at the n-th block

$$h_{m,n}(c_m) = \frac{\underbrace{\lambda}_{\text{Wavelength of the RF signal}}}{4\pi} \cdot \frac{\sqrt{\underbrace{g^t_m g^r_{m,n}}_{\text{Power gains of AP and user antennas}}}\, r_m(c_m) e^{-j2\pi(\underbrace{l^r_m}_{\text{Distance between AP and the } m\text{-th element}} + \underbrace{l^r_{m,n}}_{\text{Distance between the } m\text{-th element and the user}})/\lambda}}{l^r_m l^r_{m,n}}.$$

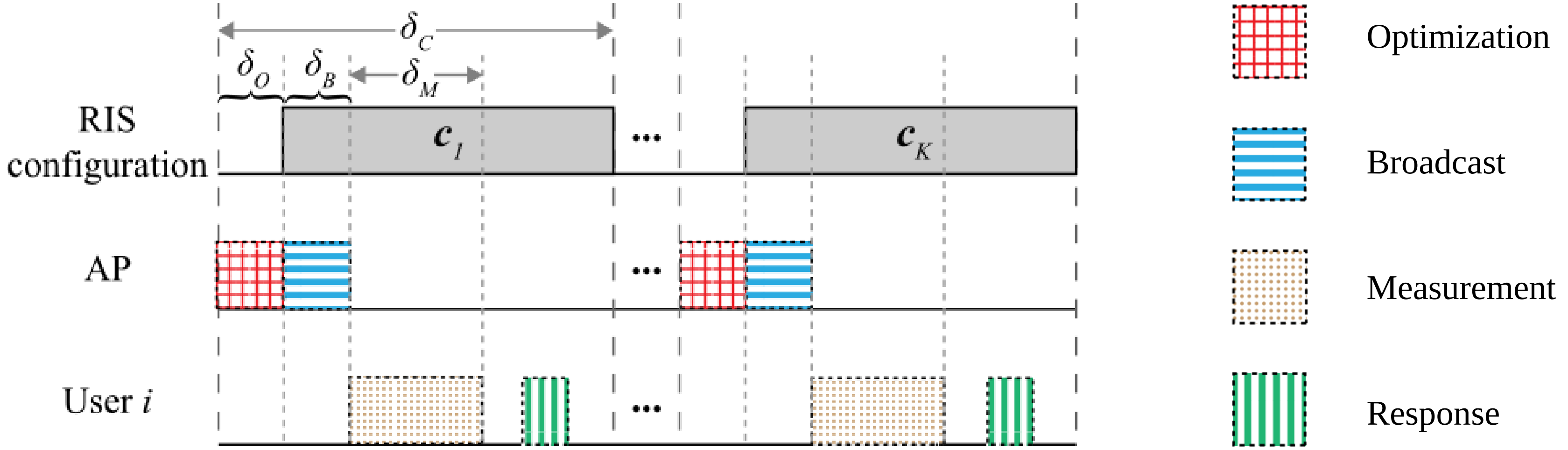
- RSS at the n-th block under configuration $\boldsymbol{c}$

$$s_n(\mathbf{c}) = \underbrace{s^t}_{\text{Transmission power of AP}} + 20 \log_{10} \left| h_{\mathrm{lo}} + \sum_{m \in \mathcal{M}} h_{m,n}(c_m) \right| + \underbrace{\xi}_{\text{Log-normal shadowing component}}.$$

Positioning Protocol

The positioning process has *K* cycles, and each cycle contains four steps:

- **Optimization:** AP selects the optimal configuration $\boldsymbol{c}_k$ for this cycle.
- **Broadcast:** AP broadcasts $\boldsymbol{c}_k$ to users and the RIS.
- **Measurement:** AP sends single-tone signal with frequency f_c, and users record the RSS under configuration $\boldsymbol{c}_k$.
- **Response:** Users send the RSS information to the AP.



Problem Formulation

Objective: Minimize the average positioning loss (weighted probabilities of false positioning) in every cycle.

$$l(\boldsymbol{c}^k) = \sum_{i\in I} \sum_{\substack{n,n'\in\mathcal{N}\\ n\neq n'}} p_{i,n}^k \gamma_{n,n'}^k \int_{\mathcal{R}_{i,n'}^k} \mathbb{P}\left(s_i^k \middle| \boldsymbol{c}^k, n\right) \cdot ds_i^k$$

- $p_{i,n}^k$: prior probability that user i is at the n-th block in the k-th cycle.
- $\gamma_{n,n'}^k$: loss parameter when the positioning result is the n'-th block while the user is at the n-th block.
- $\mathbb{P}\left(s_i^k \middle| \boldsymbol{c}^k, n\right)$: probability that user i receives s_i^k under $\boldsymbol{c}^k$ at the n-th block.
- $\mathcal{R}_{i,n'}^k$: decision region for block n'.
  - Obtained using the maximum likelihood estimation method [1].
  - If $s_i^k \in \mathcal{R}_{i,n'}^k$, we estimate that user i's position is n' in the k-th cycle.

[1] M. A. Youssef, et al, “WLAN location determination via clustering and probability distributions,” in Proc. IEEE PerCom, Fort Worth, TX, Mar. 2003.

Implementation

Metasurface module:

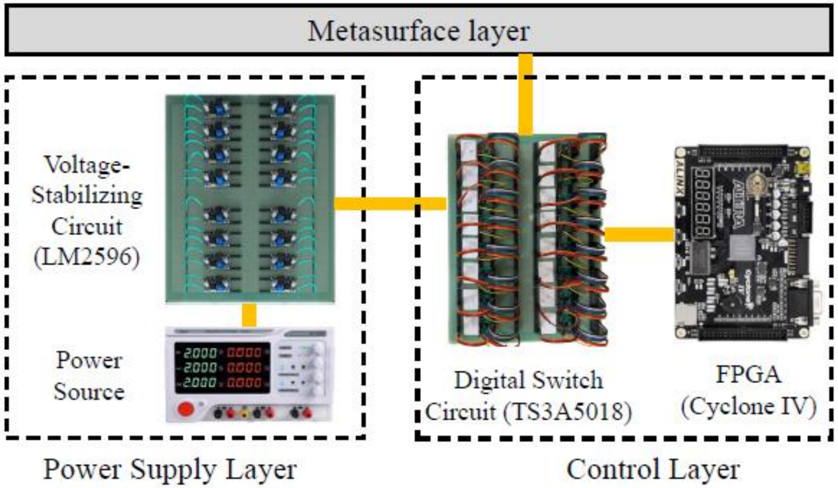
- Metasurface layer
    - Size: 69 × 69 × 0.52 cm^3
    - 4 phase shifts (interval $\frac{\pi}{2}$)
- Control layer
- Power Supply Layer

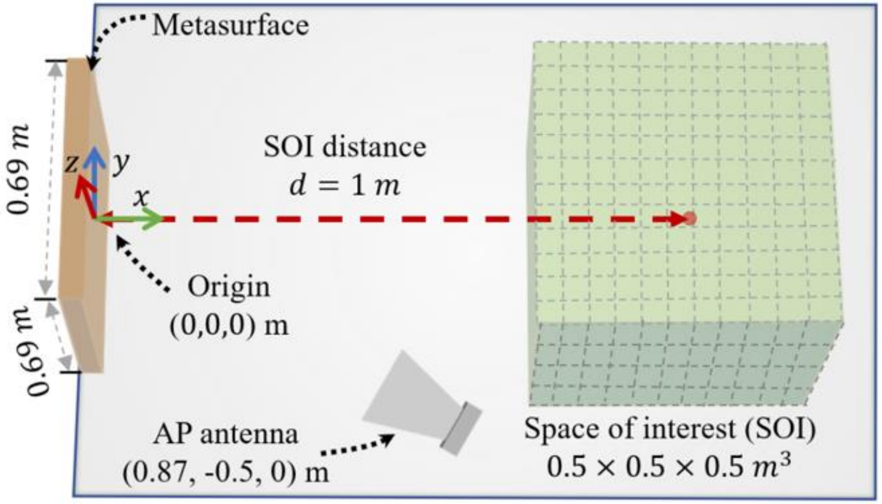
AP and user modules:

- USRPs (LW-N210)
- Horn antenna (for AP) or small polymer antenna (for users)

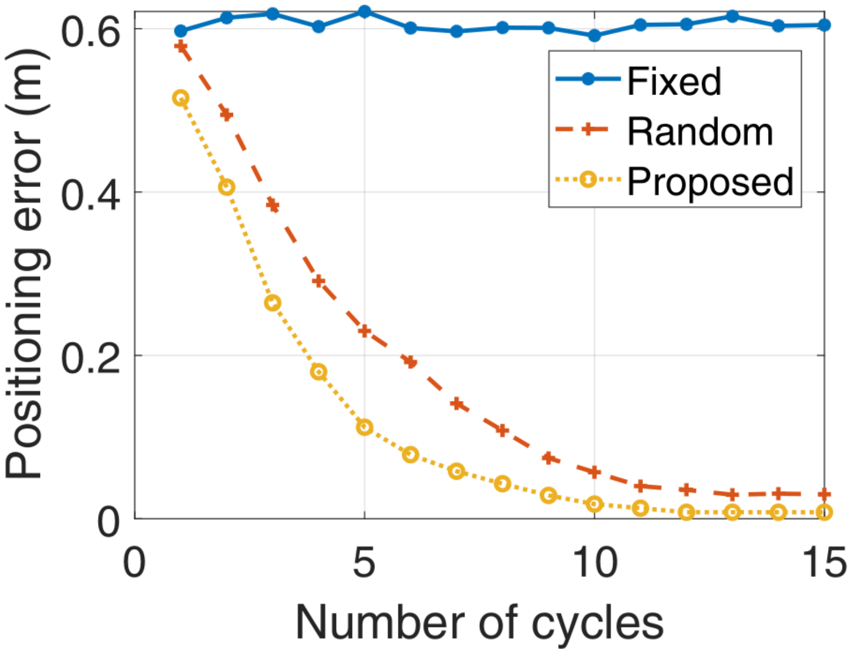
Space of interest (SOI)

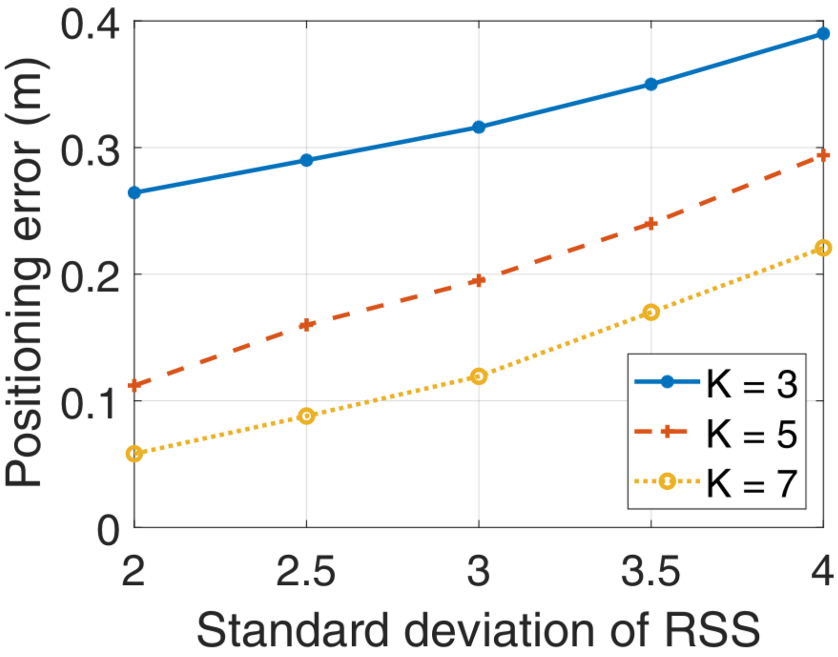
- Size: 0.5 × 0.5 × 0.5 m^3





Simulation Results



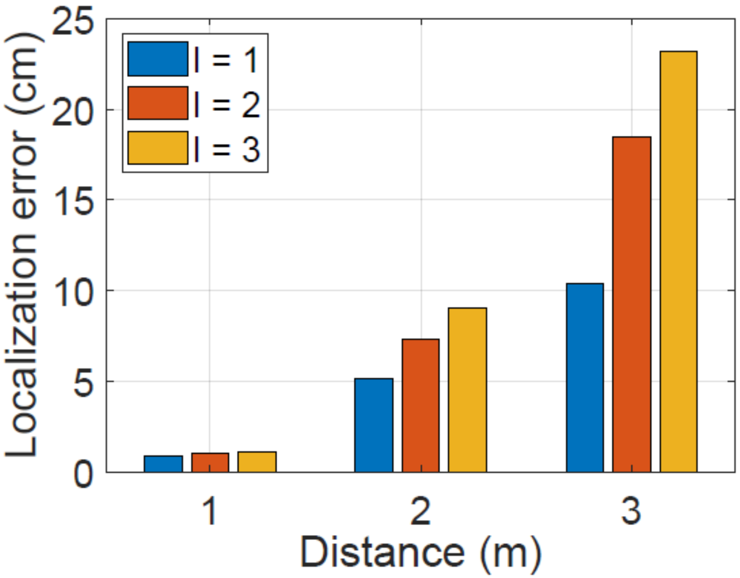


- The positioning error obtained by the proposed scheme is much lower and has a faster convergence speed than that of the random configuration scheme.
- The positioning error increases when the standard deviation increases and number of cycles *K* decreases.

Experimental Results

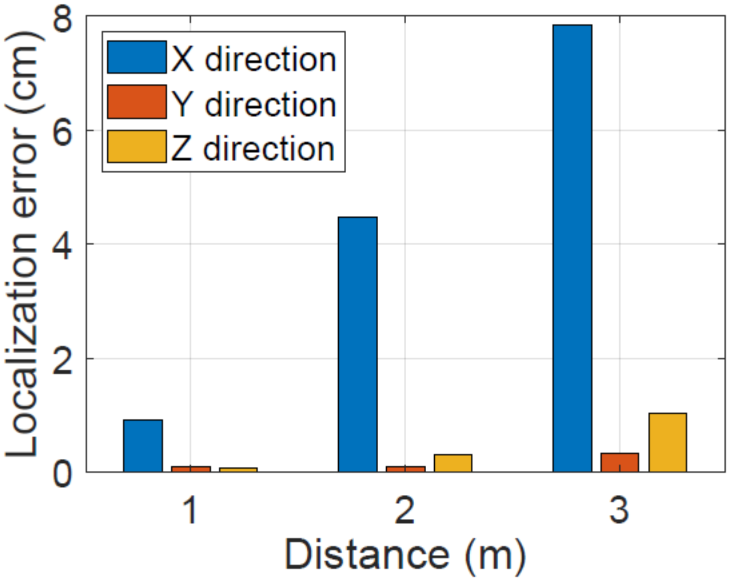
Multi-user localization:

- The localization error increases with the number of users and the SOI distance.



Accuracy in different axes:

- The localization error in the x axis is clearly larger than those in the y and z axes.
- This is because the signal correlation in the x axis (perpendicular to the metamaterials) is higher, rendering it more difficult to distinguish different blocks in the x axis.



Potential Directions

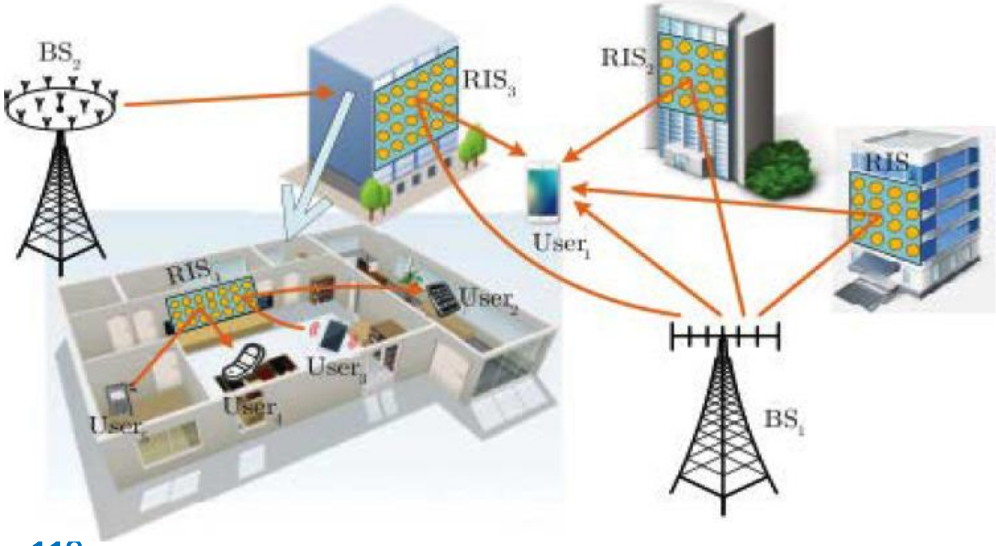
Spectrum efficiency

- Broadband Communications: OFDMA
- Full Spectrum Band Operation: mmWave, Terahertz
- Full Dimension Coverage: Transmissive-reflective meta-surface
- Implementation: Real-time environment configuration

High-resolution sensing

- Mobility and Doppler resolution
- Angular resolution and

non-uniform illumination



Other issues

- Context-awareness
- Security and privacy

Conclusions

- RIS is a promising solution for 6G providing an intelligent paradigm to shape the environments
  - Improve spectrum efficiency and network capacity
  - Extend the coverage and serve cell-edge users
  - Integrate imaging, sensing, and wireless communications
- We explore different aspects related to RIS-aided communications, sensing, and positioning
  - Limited phase shift effect and size effect
  - RIS orientation and placement for coverage extension
  - Hybrid beamforming and intelligent omni surface
  - RF sensing for various applications
  - Ubiquitous positioning

Publications (1)

RIS aided Cellular Communications

1. B. Di, H. Zhang, L. Song, Y. Li, Z. Han, and H. V. Poor, “Hybrid Beamforming for Reconfigurable Intelligent Surface based Multi-user Communications: Achievable Rates with Limited Discrete Phase Shifts”, IEEE J. Sel. Areas Commun., vol. 38, no. 8, pp. 1809-1822, Aug. 2020.
2. H. Zhang, B. Di, L. Song, and Z. Han, “Reconfigurable Intelligent Surfaces assisted Communications with Limited Phase Shifts: How Many Phase Shifts Are Enough?” IEEE Trans. Veh. Technol., vol. 69, no. 4, pp. 4498-4502, Apr. 2020.
3. B. Di, H. Zhang, L. Li, L. Song, Y. Li, and Z. Han, “Practical Hybrid Beamforming with Limited-Resolution Phase Shifters for Reconfigurable Intelligent Surface based Multi-user Communications”, IEEE Trans. Veh. Technol., vol. 69, no. 4, pp. 4565-4570, Apr. 2020.
4. M. A. Elmossallamy, H. Zhang, L. Song, K. Seddik, Z. Han, and G. Y. Li, “Reconfigurable Intelligent Surfaces for Wireless Communications: Principles, Challenges, and Opportunities,” IEEE Trans. Cognitive Commun. Netw., vol. 6, no. 3, pp. 990-1002, Sep. 2020.
5. S. Zeng, H. Zhang, B. Di, Z. Han, and L. Song, “Reconfigurable Intelligent Surface (RIS) Assisted Wireless Coverage Extension: RIS Orientation and Location Optimization,” IEEE Commun. Lett., vol. 25, no. 1, pp. 269-273, Jan. 2021.
6. Y. Chen, B. Ai, H. Zhang, Y. Niu, L. Song, Z. Han, and H. V. Poor, “Reconfigurable Intelligent Surface Assisted Device-to-Device Communications,” IEEE Trans. Wireless Commun., to appear. Arxiv: https://arxiv.org/abs/2007.00859.
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9. H. Zhang, B. Di, Z. Han, H. V. Poor, and L. Song, “Reconfigurable Intelligent Surface assisted Multi-user Communications: How Many Reflective Elements Do We Need?” IEEE Wireless Commun. Lett., under revision.
10. Y. Zhang, B. Di, H. Zhang, J. Lin, Y. Li, and L. Song, “Reconfigurable Intelligent Surface Aided Cell-free Massive MIMO Communications,” IEEE Wireless Commun. Lett., to appear.
11. S. Zhang, H. Zhang, B. Di, Y. Tan, Z. Han, and L. Song, “Reflective-Transmissive Metasurface Aided Communications for Full-dimensional Coverage Extension,” IEEE Trans. Veh. Technol., IEEE Trans. Veh. Technol., vol. 69, no. 11, pp. 13905-13909, Nov. 2020.
12. M. ElMossallamy, H. Zhang, R. Sultan, K. Seddik, L. Song, G. Y. Li, and Z. Han, “On Spatial Multiplexing Using Reconfigurable Intelligent Surfaces,” IEEE Wireless Commun. Lett., to appear.
13. S. Zhang, H. Zhang, B. Di, Y. Tan, M. D. Renzo, Z. Han, H. V. Poor, and L. Song, “Intelligent Omni-Surface: Ubiquitous Wireless Transmission by Reflective-Transmissive Metasurfaces,” IEEE Trans. Wireless Commun., submitted. Arxiv: https://arxiv.org/abs/2011.00765.
14. Y. Zhang, B. Di, H. Zhang, J. Lin, Y. Li, and L. Song, “Beyond Cell-free MIMO: Energy Efficient Reconfigurable Intelligent Surface Aided Cell-free MIMO Communications,” IEEE Trans. Cognitive Commun. Netw., to appear.
15. H. Zhang, S. Zeng, B. Di, Y. Tan, M. D. Renzo, M. Debbah, L. Song, Z. Han, and H. V. Poor, “Intelligent Reflective-Transmissive Metasurfaces for Full-Dimensional Communications: Principles, Technologies, and Implementation,” IEEE Commun. Mag., submitted.

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16. E. Shtaiwi, H. Zhang, M. Youssef, A. Abdelhadi, and Z. Han, “Channel Estimation Approach for RIS Assisted MIMO Systems,” IEEE Trans. Cognitive Commun. Netw., under revision.
17. R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, “Reconfigurable Holographic Surface: Holographic Beamforming for Metasurface-aided Wireless Communications,” IEEE Trans. Veh. Technol., submitted.
18. S. Zeng, H. Zhang, B. Di, Y. Tan, Z. Han, H. V. Poor, and L. Song, “Reconfigurable Intelligent Surfaces in 6G: Reflective, Transmissive, or Both?”, IEEE Commun. Lett., under revision.
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21. E. Shtaiwi, H. Zhang, A. Abdelhadi, and Z. Han, “RIS-Assisted mmWave Channel Estimation Using Convolutional Neural Networks,” in Proc. IEEE WCNC Workshops, Nanjing, China, Mar. 2021.
22. Y. Chen, B. Ai, H. Zhang, Y. Niu, L. Song, Z. Han, and H. V. Poor, “Reconfigurable Intelligent Surface Assisted D2D Networks: Power and Discrete Phase Shift Design,” in Proc. IEEE GLOBECOM, Taipei, Taiwan, Dec. 2020.

Publications (4)

RIS aided RF Sensing

1. J. Hu, H. Zhang, B. Di, L. Li, L. Song, Y. Li, Z. Han, and H. V. Poor, “Reconfigurable Intelligent Surfaces based RF Sensing: Design, Optimization, and Implementation,” IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2700-2716, Nov. 2020.

2. J. Hu, H. Zhang, K. Bian, M. D. Renzo, Z. Han, and L. Song, “MetaSensing: Intelligent Metasurface Assisted RF 3D Sensing by Deep Reinforcement Learning,” ,” IEEE J. Sel. Areas Commun., under review.

3. H. Zhang, H. Zhang, B. Di, K. Bian, Z. Han, and L. Song, “Towards Ubiquitous Positioning by Leveraging Reconfigurable Intelligent Surface,” IEEE Commun. vol. 25, no. 1, pp. 284-288, Jan. 2021.

4. H. Zhang, J. Hu, H. Zhang, B. Di, K. Bian, Z. Han, and L. Song, “MetaRadar: Indoor Localization by Reconfigurable Metamaterials,” IEEE Trans. Mobile Comput., to appear. Arxiv: https://arxiv.org/abs/2008.02459.

5. J. Hu, H. Zhang, K. Bian, Z. Han, H. V. Poor, and L. Song, “HoloSketch: Semantic Segmentation by Radio Environment Reconfiguration,” IEEE Trans. Mobile Comput., submitted.

6. H. Zhang, H. Zhang, B. Di, K. Bian, Z. Han, and L. Song, “MetaLocalization: Reconfigurable Intelligent Surface Aided Multi-user Wireless Indoor Localization,” IEEE Trans. Wireless Commun., under revision.

Thanks for your attending