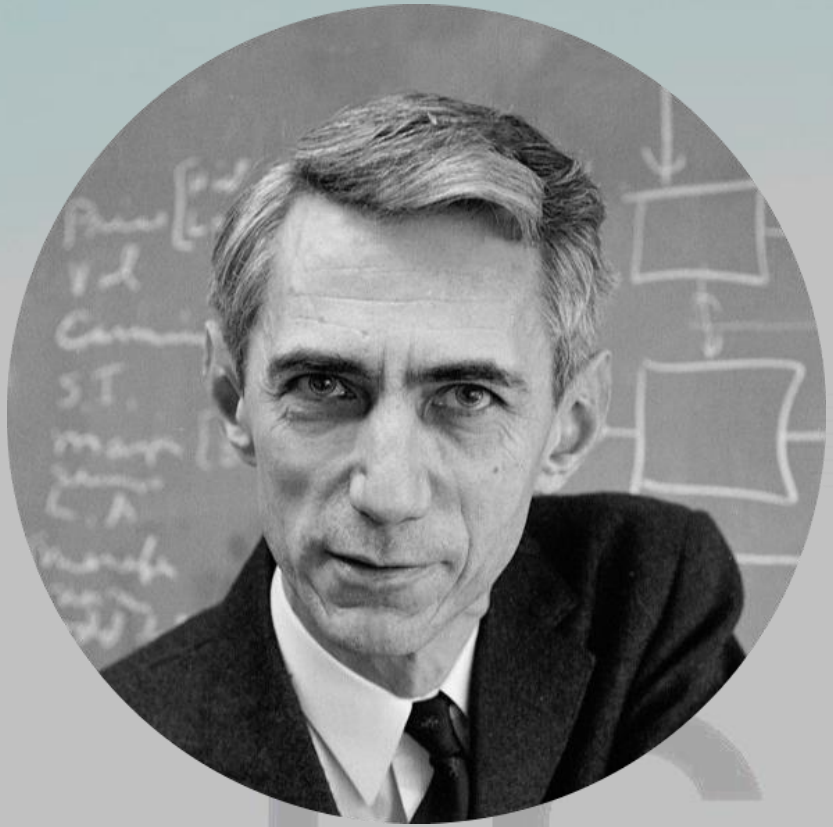
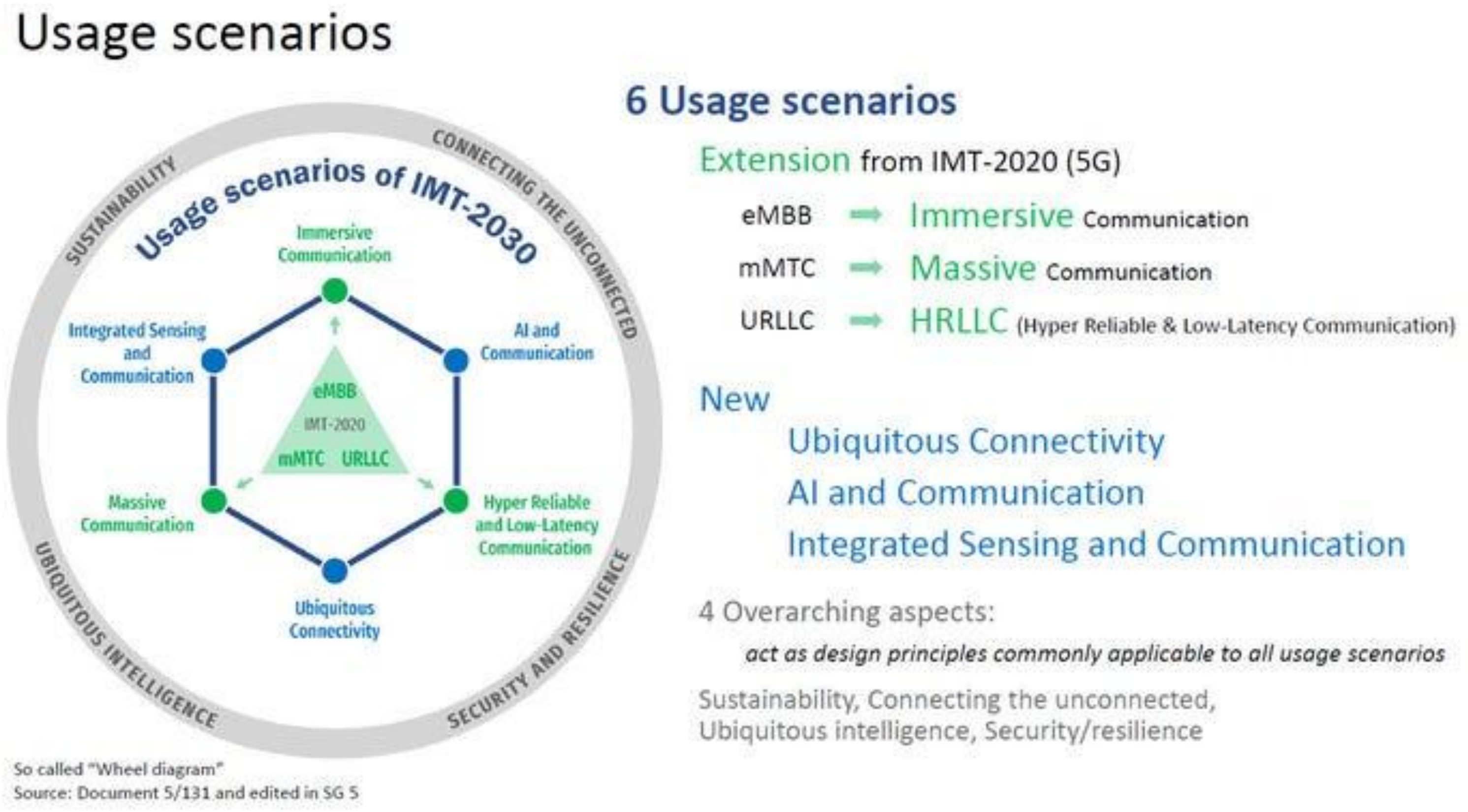


From 5G to 6G: Applications and Resource Allocation

Zhu Han
Electrical and Computer Engineering Department, University of Houston
John and Rebecca Moores Professor, IEEE/AAAS/ACM Fellow

Outline

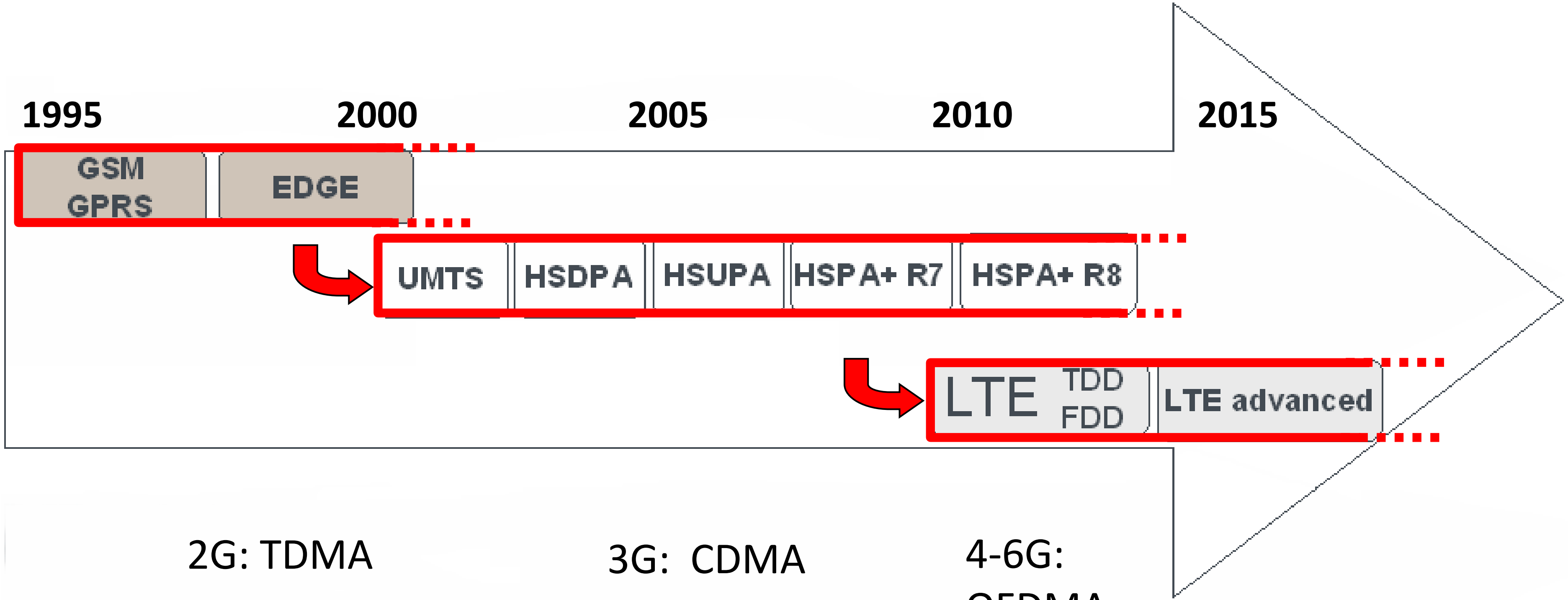
- Introduction of 5G to 6G
  - 5G Triangle
  - 6G Hexagon
  - Prototype demos
    - Smart Surface
    - GAI + Semantic
    - ISAC
    - SAGIN



- Resource Allocation in Wireless Networks
  - Assorted Game Theoretical Approaches for Distributed Management
- Conclusions

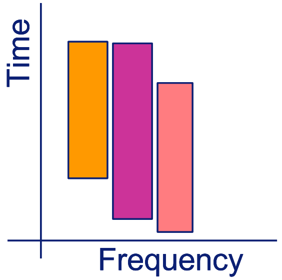
Standardization Facilitates Technology Evolution

2G-4G: Each new evolution builds on the established market of the previous

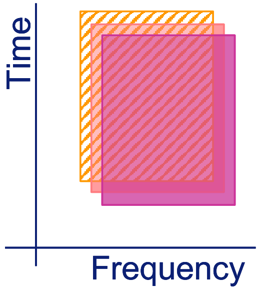


1G: Analog

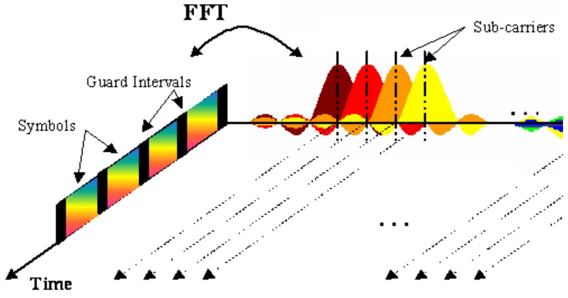
2G: TDMA



3G: CDMA



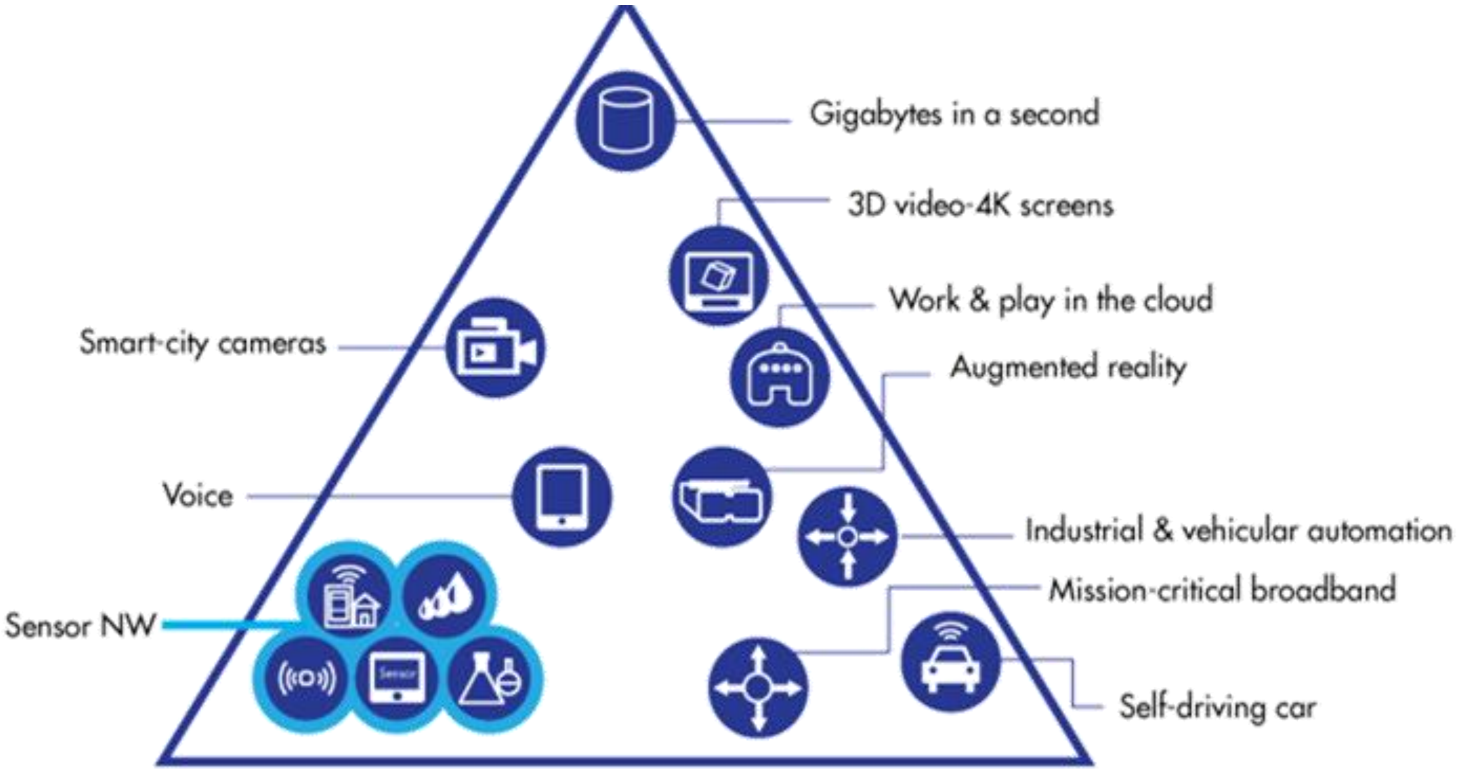
4-6G:
OFDMA



5G, 6G and Beyond

Capacity Enhancement

eMBB (Gbps)



mMTC

Massive Connectivity

(1M/km^2)

uRLLC

Ultra-high Reliability & Low Latency (1ms)

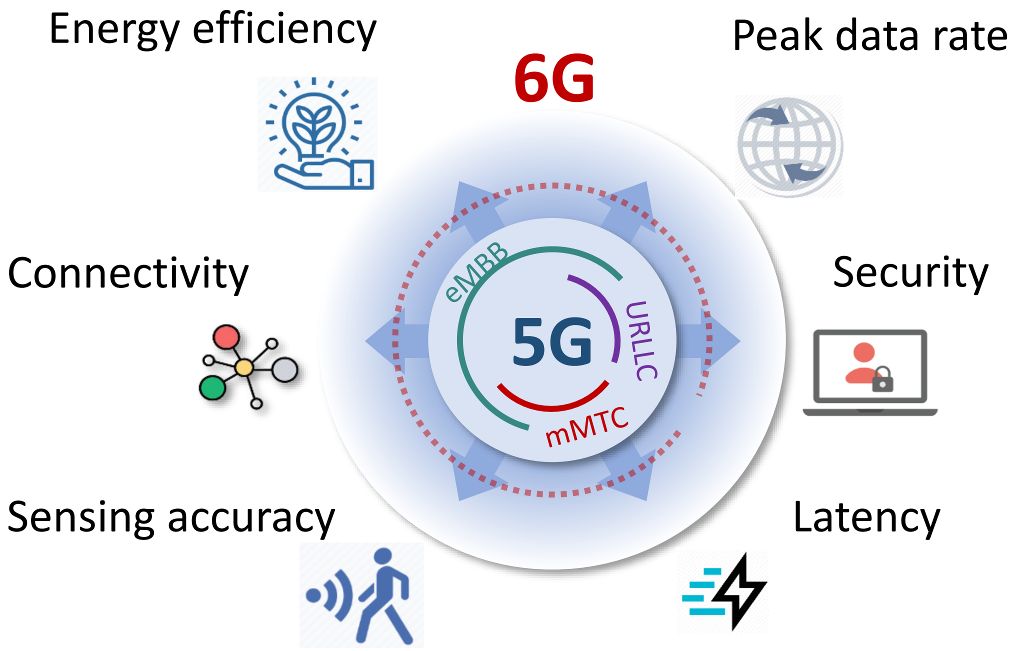
Assorted Techniques

- Massive MIMO
- mmWave
- Ultra-dense networks
- D2D
- Software defined network
- Network virtualization
- D-RAN and C-RAN
- Small cell
- Edge/Fog computing
- NOMA
- LTE-U and LAA
- …

Demo1: RHS MmWave Ultra-massive MIMO

5G, 6G and Beyond

VR for education
Metaverse



Autonomous driving
Environment sensing

AR for surgery

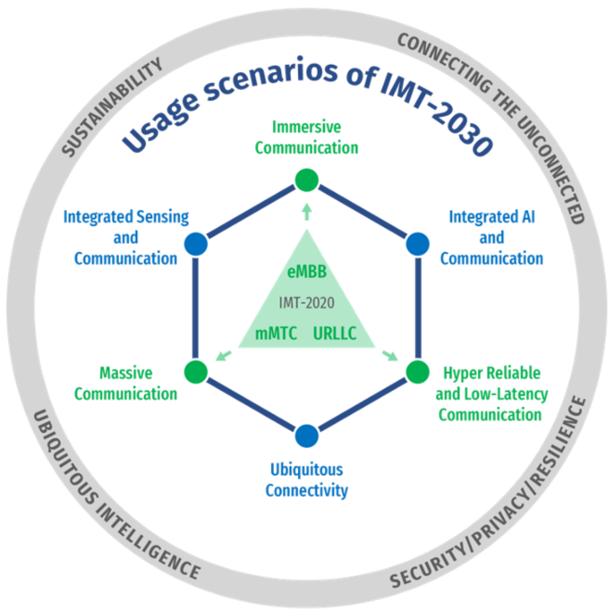
Auto-manufacturing

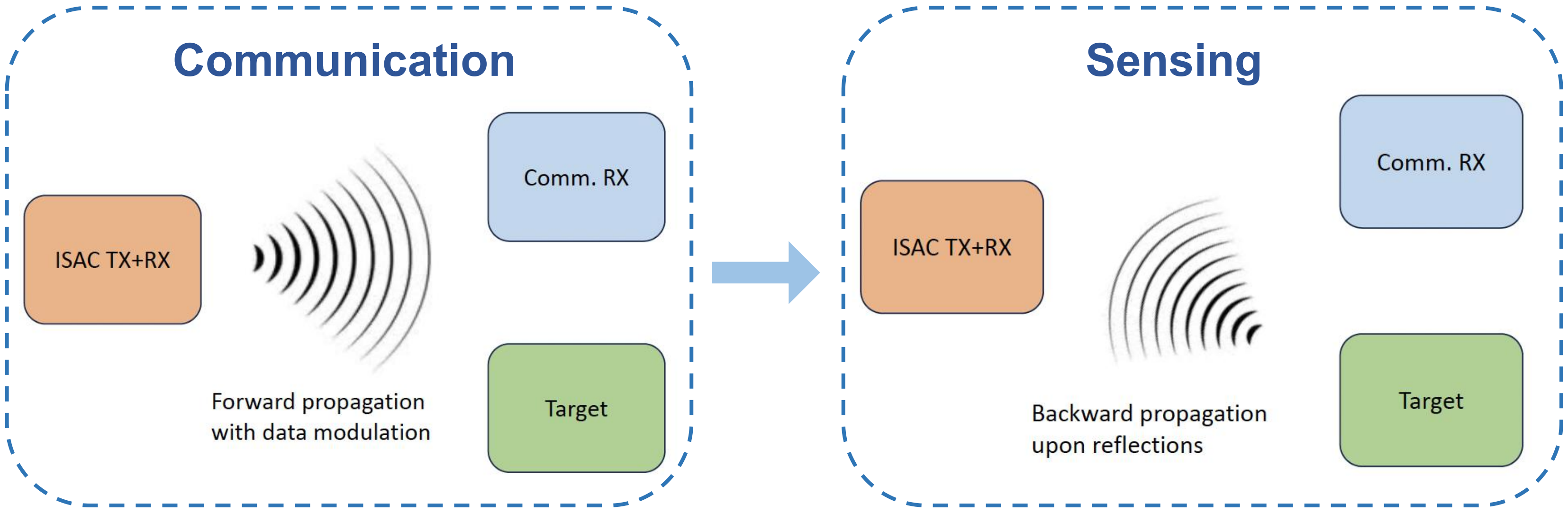
E-health

Smart home

6G-1. Integrated Sensing and Communications (ISAC)

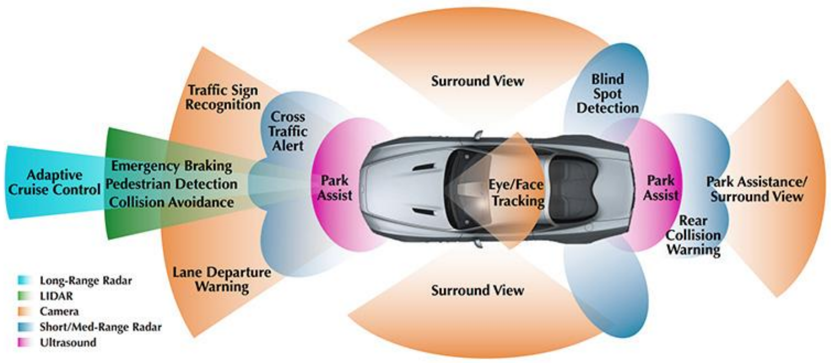
- In ISAC, the waveform completes communications in the forward propagation, and then sensing in the backward propagation.
- ISAC is one of ITU usage scenarios of future 6G systems



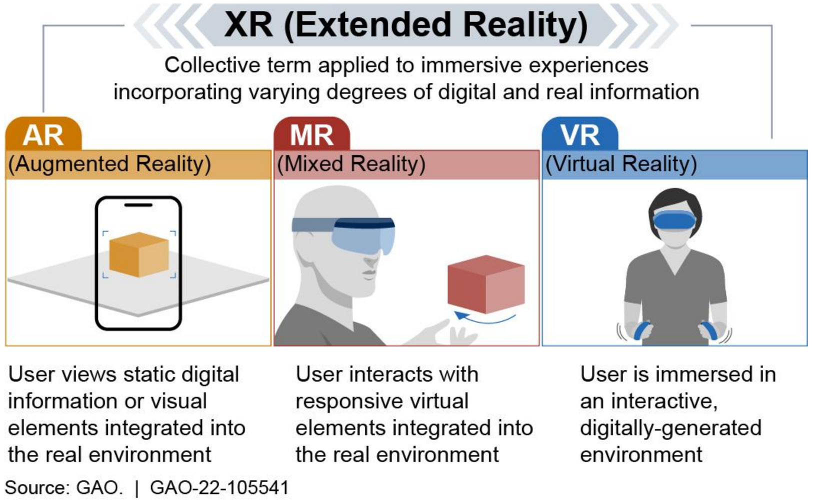


ISAC Use Cases

Autonomous Vehicles

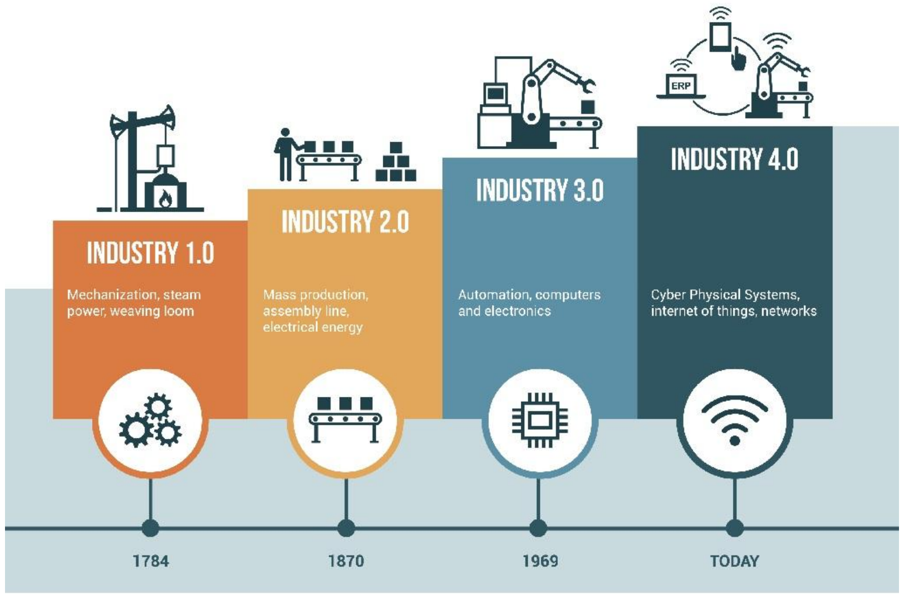


Extended Reality (XR)



Security and Surveillance

Internet of Things



Space Communications

Other Applications

- Entertainments
- Maritime
- Public Safety
- Disaster management
- Agriculture
- Smart Home/City
- Healthcare
- …

Demo2: 6G Integrated Sensing and Communication

IEEE MILCOM' 24 Demo

Waveform Shaping in Integrated Sensing and Communications

Henglin Pu*, Salma Sultana#, Husheng Li*, Zhu Han#, and H. Vincent Poor$
*Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA
#Electrical and Computer Engineering Department, University of Houston, Houston, TX, USA
$Electrical Engineering Department, Princeton University, Princeton, NJ, USA

PURDUE UNIVERSITY

UNIVERSITY OF HOUSTON

PRINCETON UNIVERSITY

6G-2. AI and Communication

What is Generative AI?

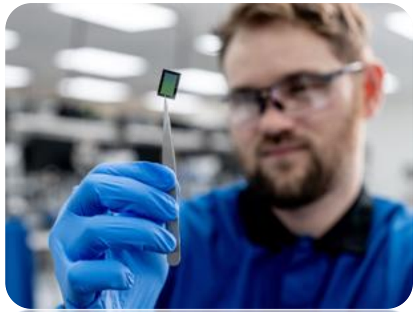
AI that creates new, original content (images, text, music, environments).

Why Generative AI?

Enables novel experiences and increased user engagement.

Generative AI Examples

Procedurally generated virtual worlds, personalized avatars, dynamic landscapes.



A New Molecular Language for Generative AI in Small-Molecule Drug Discovery

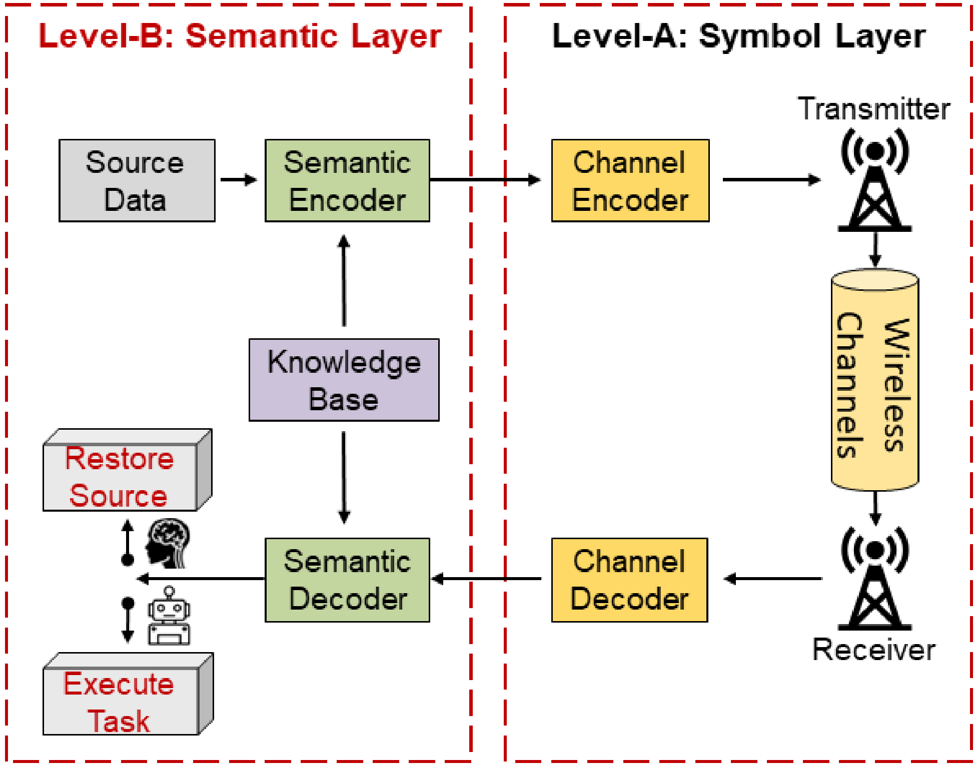
Video Sessions for Accelerated Development

Scaling Generative AI with End-to-End Platform Solutions

Conventional vs. Semantic Communication

- Shannon-Weaver three-level communications
  - ➢Level A: Transmission of symbols (technical problem)
  - ➢Level B: Semantic exchange of source information (sematic problem)
  - ➢Level C: Effects of semantic information exchange (effectiveness problem)

- Semantic system architecture
  - ➢ Semantic knowledge base: perceive semantic features
  - ➢ Semantic encoder: extract semantics from input data
  - ➢ Semantic decoder: restore semantics per request of tasks

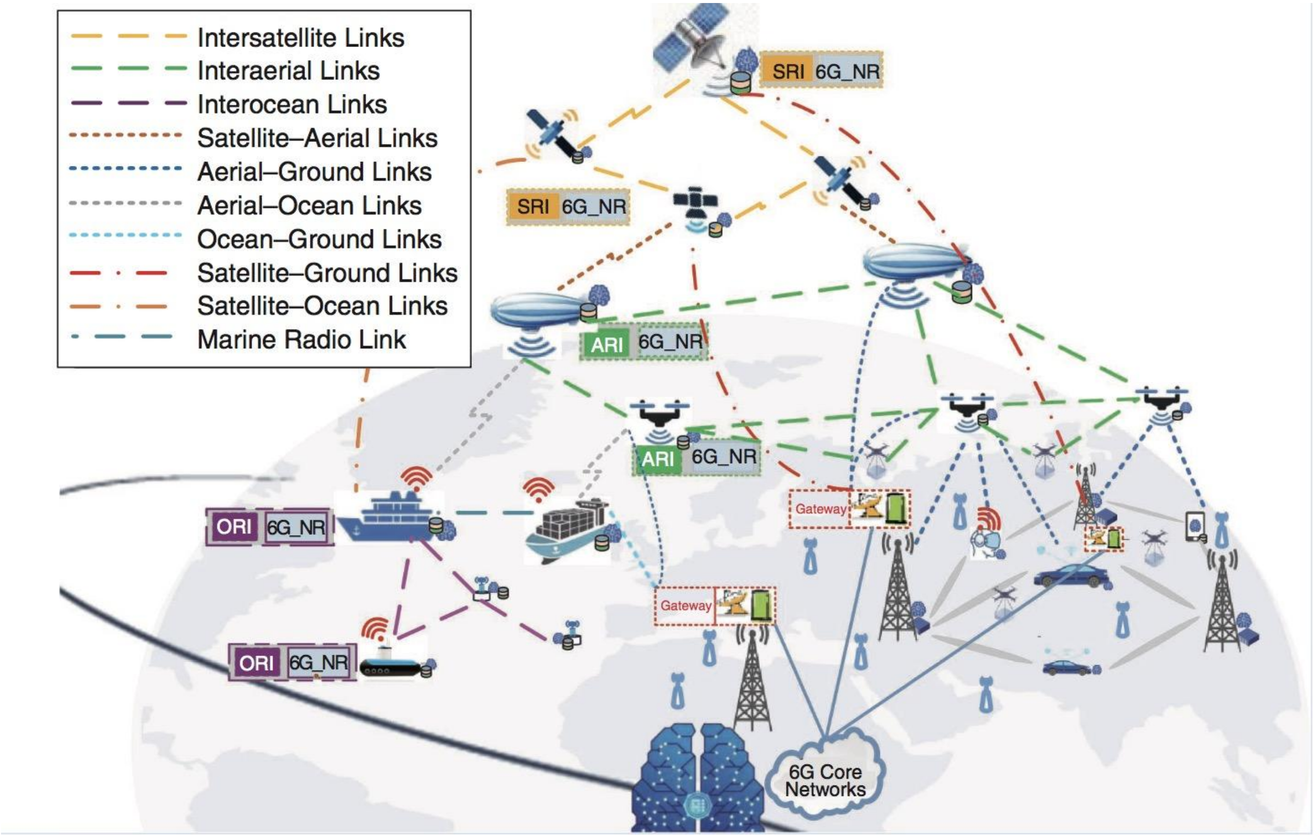


Demo3: Generative AI Enabled Semantic Communication

6G-3. Ubiquitous Connectivity: Aerial Access Network

An integrated network consisting of aerial vehicles and satellites

- Unmanned Air Vehicle (UAV)
- High-altitude platform (HAP)
- Satellite
  (belong to AAN in a generalized sense)
- Terrestrial terminal
  (handhold device or access point)
- Gateway (to core network)



Source: Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, “6G wireless networks: Vision, requirements, architecture, and key technologies,” *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, Sep. 2019.

Space-Air-Ground Integrated Network (SAGIN) Vehicle Classification

	UAV	HAPS	Satellite
			
Height	600m-18km	17-22 km	>160km
Time duration	Minutes to hours	hours to months	Years
Coverage	Small and changing	Medium and fixed	Large and periodic
Energy	Lithium battery	Solar panel, battery	Solar panel, battery
Controller	Ground and HAP	Satellite and ground	Ground
Applications	Sensing Communication Surveillance	Real-time monitoring Communication relay Emergency recovery Rocket launch platform	Communication Observation Navigation Weather Astronomy

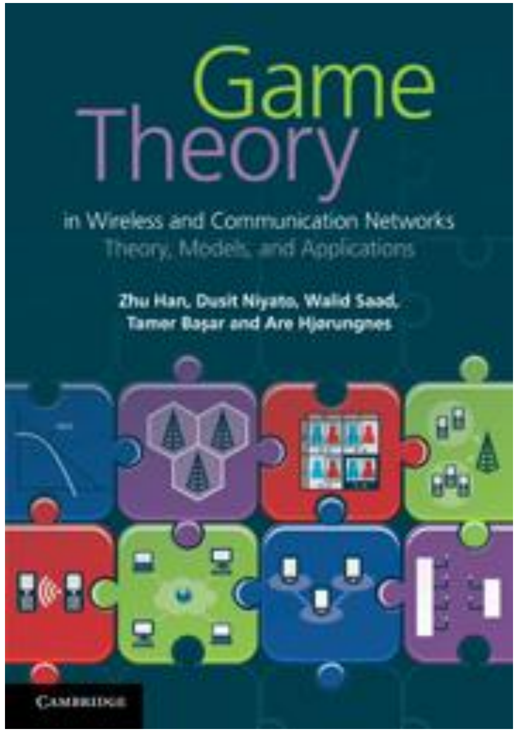
Demo4: SAGIN-4C-6G

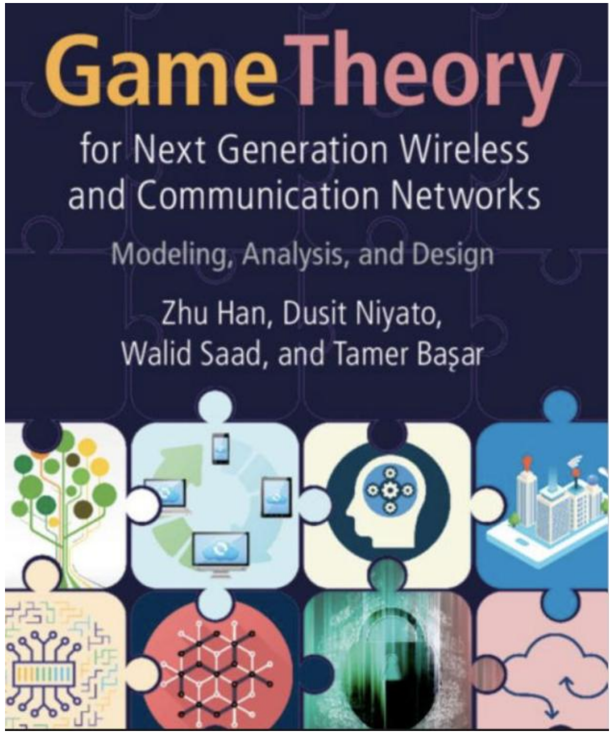
Outline

- Introduction of 5G to 6G
- Resource Allocation in Wireless Networks
- Assorted Game Theoretical Approaches
- Conclusion

Zhu Han, Dusit Niyato, Walid Saad, Tamer Basar, and Are Hjorungnes, *Game Theory in Wireless and Communication Networks: Theory, Models and Applications*, Cambridge University Press, UK, 2011.

Zhu Han, Dusit Niyato, Walid Saad, and Tamer Basar, Game Theory for Next-Generation Wireless and Communication Networks: Modeling, Analysis, and Design, Cambridge University Press, UK, 2017.





Resource Allocation for Networks

$$\text{MAXIMIZE} \quad Y = f(X_1, X_2)$$

SUBJECT TO:

$$\left.\begin{array}{l} g(X_1, X_2) \leq 0 \\ h(X_1, X_2) = 0 \end{array}\right\}$$

$$X = \begin{vmatrix} X_1 \\ X_2 \end{vmatrix}$$

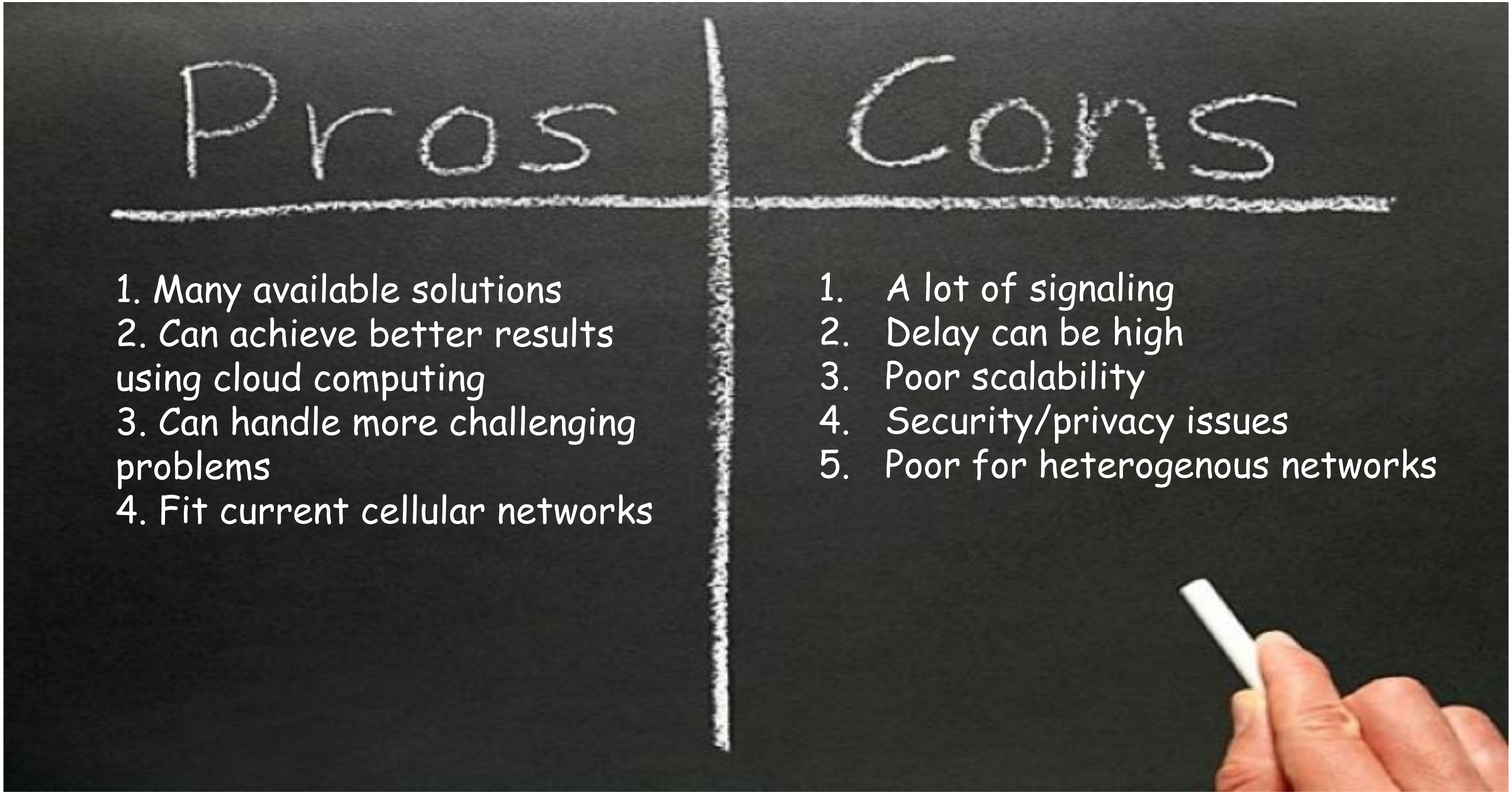
Objective:
What to be maximized or minimized
e.g. system capacity, overall power…

Constraints:
Nonnegotiable conditions to be met
Negotiable but desirable conditions
e.g. bandwidth, maximal TX power…

Decision variables:
parameter for designers to change
e.g. power, channel…
Integer vs. Continuous variables

Typically NP hard

Centralized Solutions and it Dilemmas



Pros

1. Many available solutions
2. Can achieve better results using cloud computing
3. Can handle more challenging problems
4. Fit current cellular networks

Cons

1. A lot of signaling
2. Delay can be high
3. Poor scalability
4. Security/privacy issues
5. Poor for heterogenous networks

Distributed Solutions and it Dilemmas

Each user optimizes its own:

User 1: $\max_{X_1} \; Y_1 = f_1(X_1 \mid X_2)$
s.t. $g(X_1, X_2) \le 0$
$h(X_1, X_2) = 0$

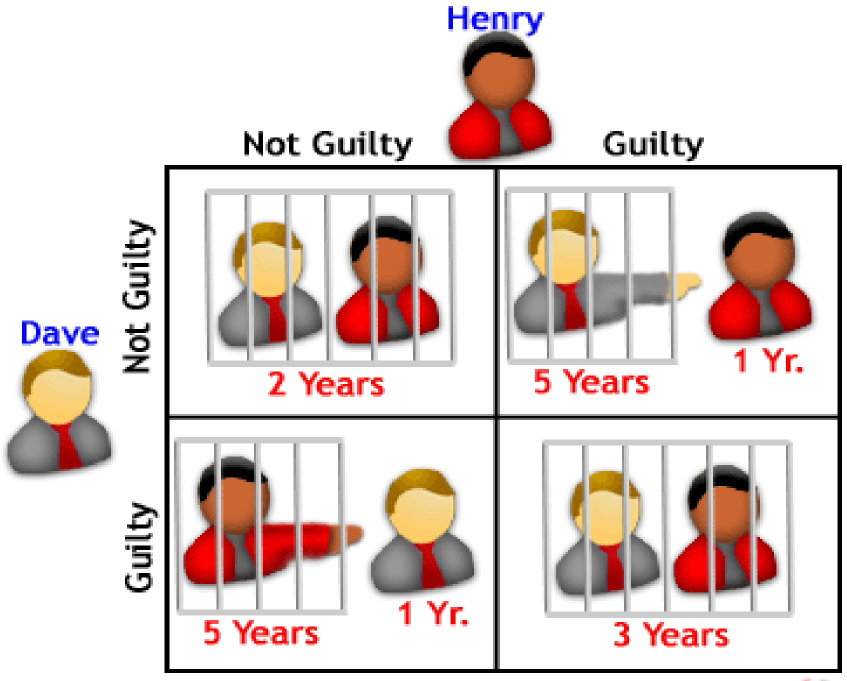
User 2: $\max_{X_2} \; Y_2 = f_2(X_2 \mid X_1)$
s.t. $g(X_1, X_2) \le 0$
$h(X_1, X_2) = 0$

Nash Equilibrium: No player can improve its payoff by **unilaterally** changing its strategy, given that the other players' strategies remain fixed, i.e.,

$$f_i(X_i^*, X_{-i}^*) \ge f_i(X_i \;, X_{-i}^*), \forall X_i \in S_i, \text{ i=1,2}$$

where S_i is the feasible set satisfying the constraints.

The Price of Anarchy: Compared with the centralized optimal solution, distributed solution will have possible significant performance loss.



Game Theoretical Approaches

- Non-cooperative static games:
  - Sports: zero sum game. Boxing: example of equilibrium
- Repeated games: play multiple times
  - **Threat of punishment** by repeated game. MAD: Nobel prize 2005.
- Evolutional games:
  - Evolutionary stable strategy
  - Replicator dynamic
- Bayesian games
  - Incomplete/private information
  - Belief
- Bounded rationality
  - Prospect Theory, Nobel Prize 2002
- Auction theory
  - Nobel Prize 1996

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Games in Strategic (Normal) Form

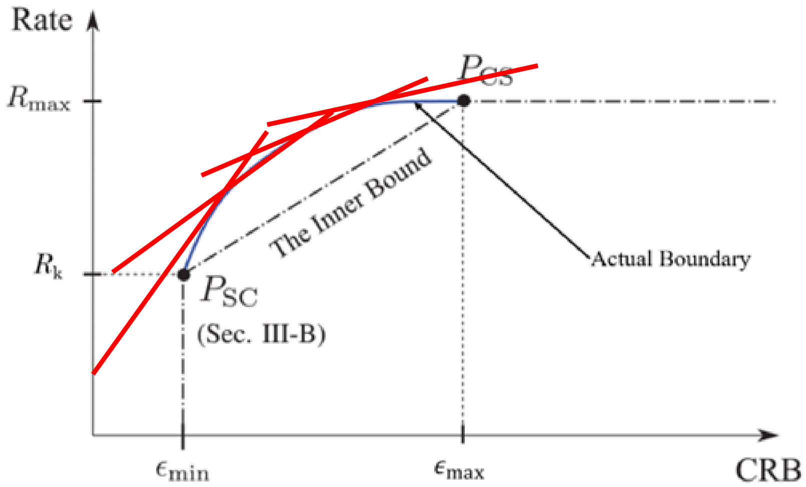
- A game in strategic (normal) form is represented by three elements
  - A finite set of players, N
  - The set of available strategies for player i, S_i
  - The utility (payoff) function for player i, u_i
- $\mathbf{s} = (s_i , \mathbf{s}_{-i})$ is the strategy profile, where s_i in S_i is the strategy of player i, and $\mathbf{s}_{-i}$ the vector of strategies of all players except i
- Note that one user's utility is a function of both this user's and others' strategies
- ***Complete Information Game:*** If all elements of the game are common knowledge
- ***Incomplete Information Game:*** The players may not know the identities of all other players, their payoffs or their strategies

Nash Equilibrium (2)

- Does the Nash equilibrium always exist? Low efficiency: Price of Anarchy
- ***Pareto Optimality:*** A measure of efficiency
  - A payoff vector **x** is Pareto optimal if there does **not** exist any payoff vector **y** such that

$$\mathbf{y} \geq \mathbf{x}$$

    with at least one strict inequality for an element y_i
- Someone's improvement must hurt others
- Multi-objective such as ISAC



Pareto optimal

Nash equilibrium

	P2 Quiet	P2 Fink
P1 Quiet	1,1	4,0
P1 Fink	0,4	3,3

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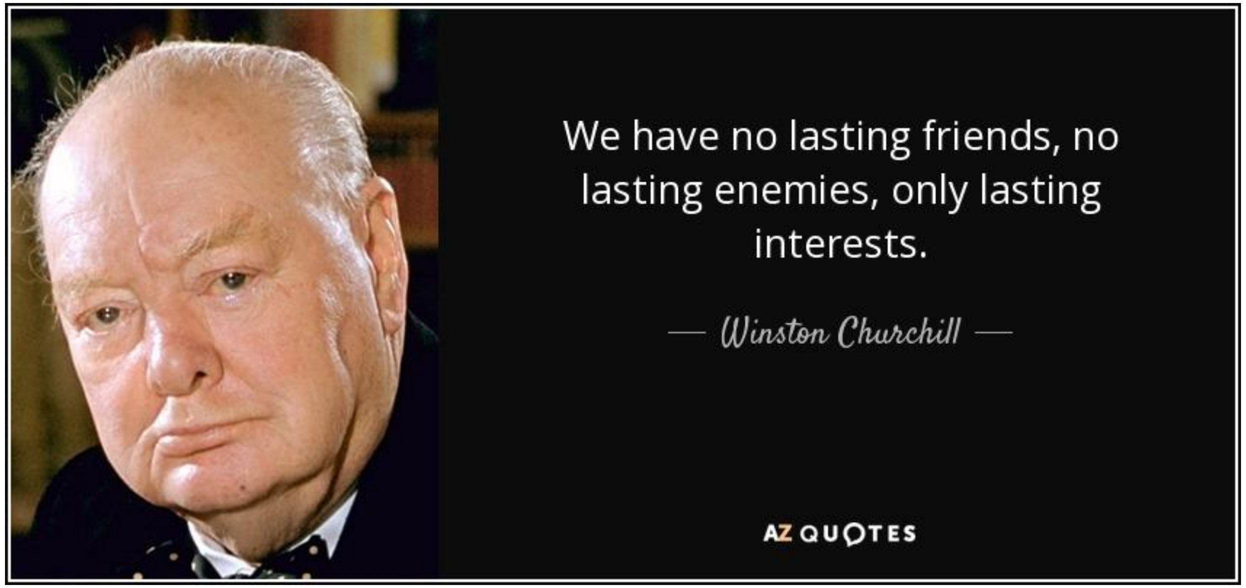
Coalitional Games: Preliminaries

Definition of a coalitional game (*N,v*)

- A set of players ***N***, ***a coalition*** S is a group of cooperating players (subset of N)
- Worth (utility) of a coalition ***v***
  - **Payoff v(S)** represents the gain resulting from a coalition S in the game (N,v)
  - **v(N)** is the worth of forming the coalition of all users, known as the **grand coalition**
- User payoff x_i : the portion of ***v(S)*** received by a player ***i*** in coalition S

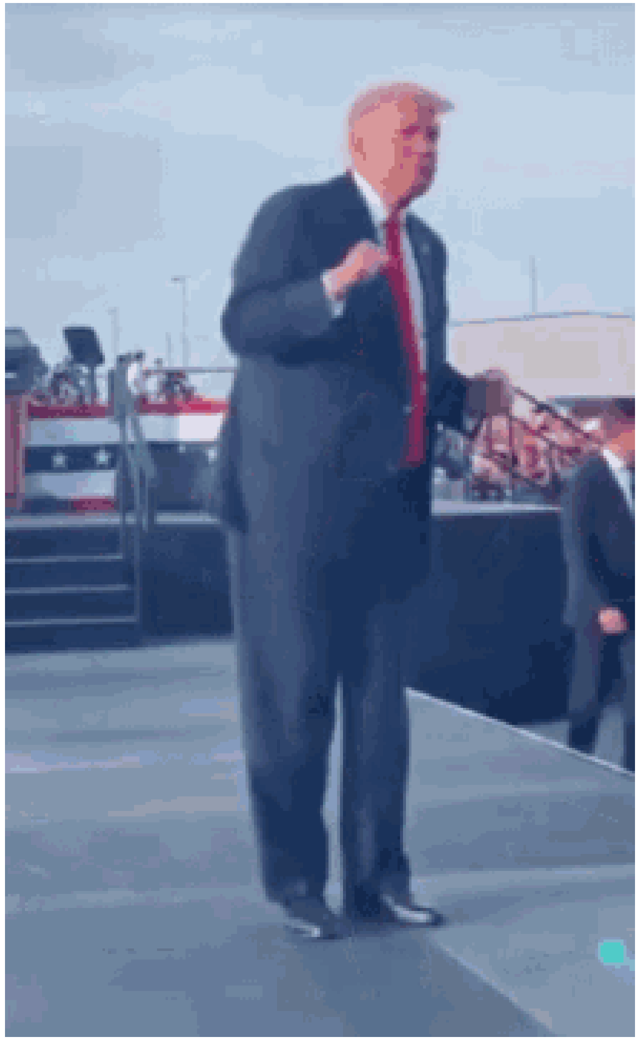


An example coalitional game

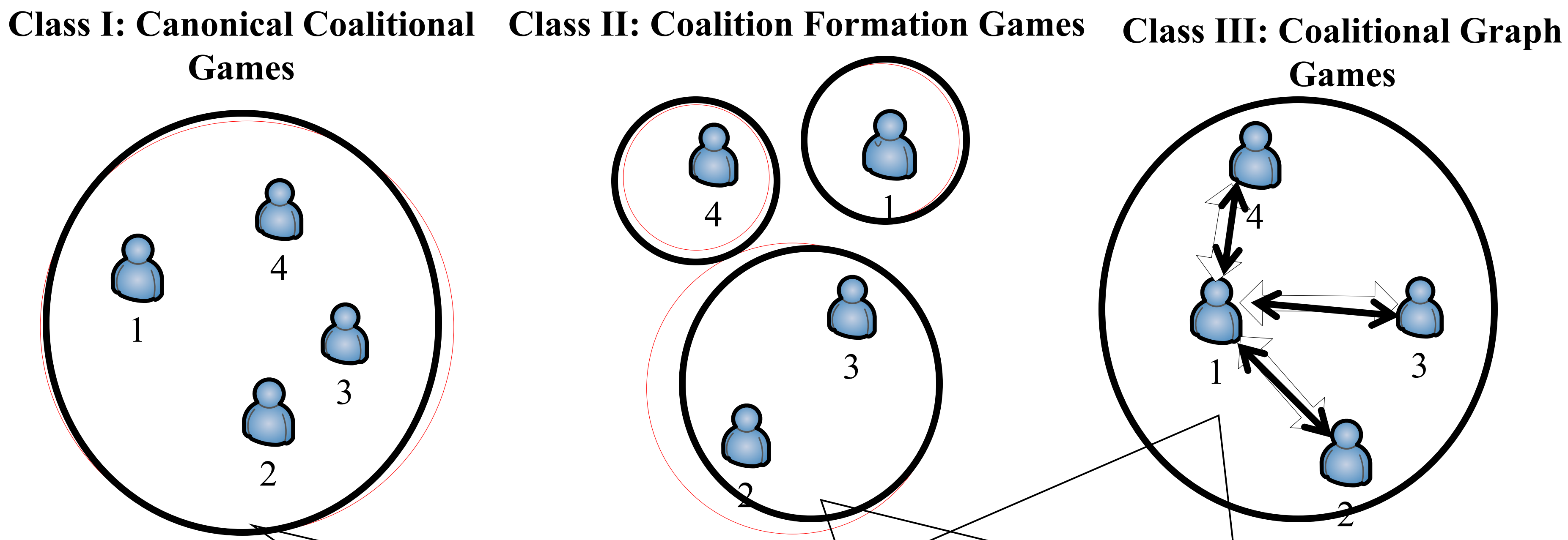
- Example of a coalition game: Majority Vote

$$v(S) = \begin{cases} 1, & \text{if } |S| > |N|/2; \\ 0, & \text{otherwise.} \end{cases}$$

  - President is elected by majority vote
  - A coalition consisting of a majority of players has a worth of 1 since it is a decision maker
  - Value of a coalition does not depend on the external strategies of the users
    - This game is in characteristic function form
  - How to divide the value of winning
    - Transferable utility
    - Non-transferable utility



A New Classification (My Career Award 2010)



- The grand coalition of all users is an optimal structure.
-Key question "How to stabilize the grand coalition?"
-Several well-defined solution concepts exist.

- The network structure that forms depends on gains and costs from cooperation.
-Key question "How to form an appropriate coalitional structure (topology) and how to study its properties?"
- More complex than Class I, with no formal solution concepts.

- Players' interactions are governed by a communication graph structure.
-Key question "How to stabilize the grand coalition or form a network structure taking into account the communication graph?"
- Solutions are complex, combine concepts from coalitions, and non-cooperative games

Coalition Formation: Merge and Split

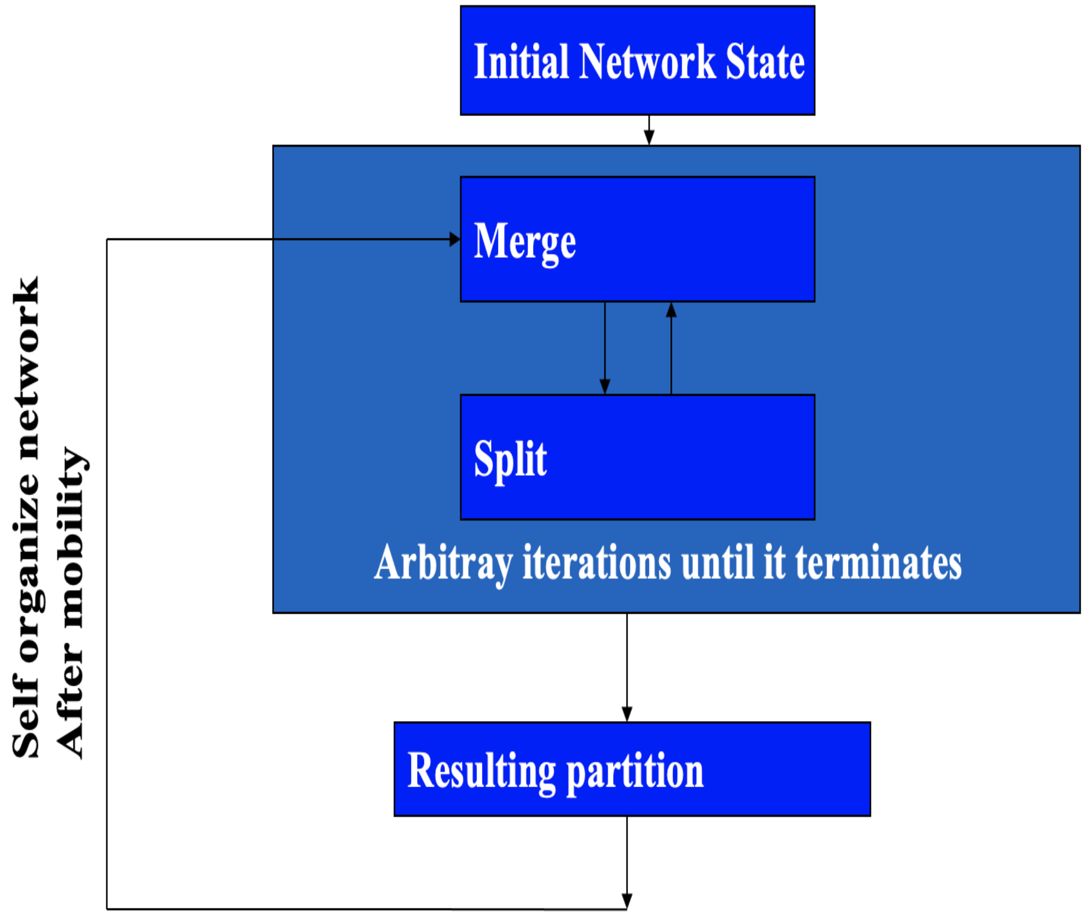
- **Merge rule**: merge any group of coalitions where

$$\{\cup_{j=1}^{l} S_j\} \triangleright \{S_1, \ldots, S_l\}$$

- **Split rule**: split any group of coalitions where

$$\{S_1, \ldots, S_l\} \triangleright \{\cup_{j=1}^{l} S_j\}$$

- A decision to merge (split) is an agreement between all players to form (break) a new coalition
  - Socialist (social well fare improved by the decision)
  - Capitalist (individual benefit improved)
- Solve the integer problem distributively

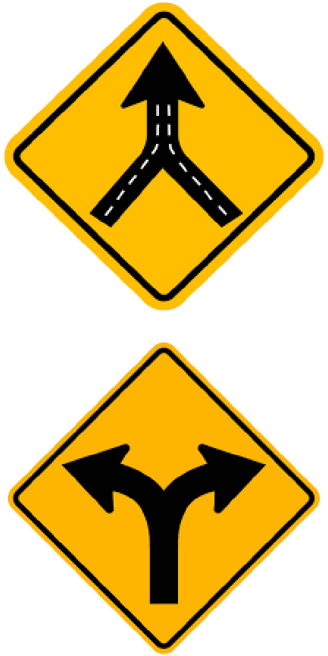


Academia Collaboration

Find mutual benefits

Gain a card by each cooperation

Merge and Split



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Matching Theory Basics

Traditional matching needs O(N^3) Hungarian method to have the optimal solution

Matching game provide suboptimal simple solution

Basic elements (***Stable Marriage***):

- ***Agents***: A set of men, and a set of women;
- ***Preference list:*** A sorted list of men/women based on her/his preferences;
- ***Blocking pair (BP)*** (m,w):

  1). m is unassigned or prefers w to his current partner;

  2). w is unassigned or prefers m to her current partner;
- ***Stable matching***: A matching admit no BPs.
- ***Gale-Shapley*** Algorithm: find a stable matching O(N)

Alvin E. Roth and Lloyd S. Shapley shared the 2012 Nobel Prize in Economic Science

Matching Theory: Gale-Shapley Algorithm

We reach a stable marriage fast!

Adam

Geeta, Heiki, Irina, Fran

Bob

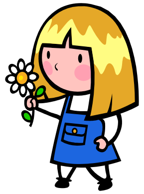
Irina, Fran, Heiki, Geeta

Carl

Geeta, Fran, Heiki, Irina

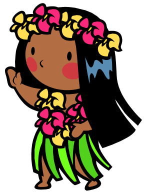
David

Irina, Heiki, Geeta, Fran

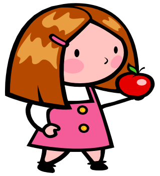


Fran

Geeta

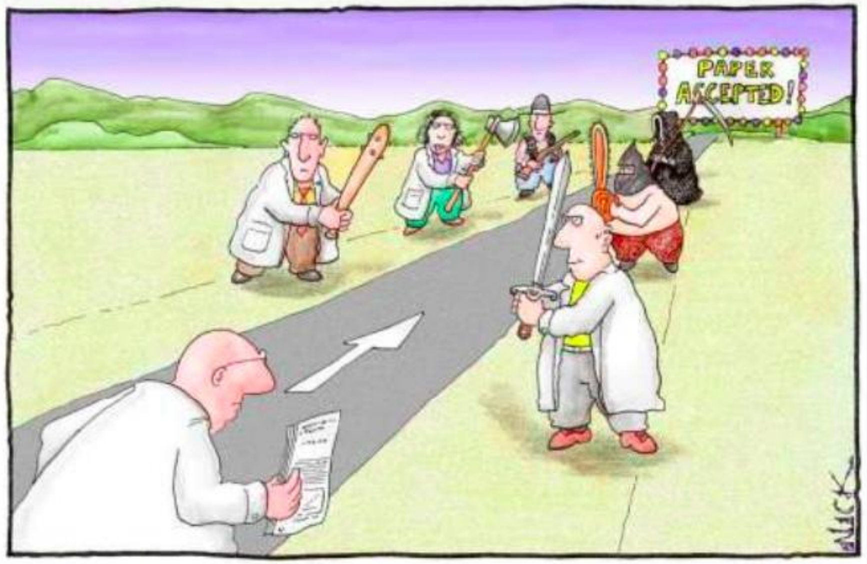


Heiki



Irina

Reviewer Assignment Problem



Most scientists regarded the new streamlined
peer-review process as 'quite an improvement.'

It is a bad paper and, as a reviewer, I should reject it,
but it cites five of my own papers...

Example: Toyota Edge Computing

- Challenges:
  - Once the end devices are invited, they will unconditionally take part in the federated learning tasks which ignores their willingness.
    - Computation cost, remained energy…
  - There are many available edge nodes in a MEC network, how to parallelly perform multiple federated learning tasks needs to be considered.
  - Information exchanging cannot be done entirely in large scale IoTs scenarios.
  - Matching Game Framework with incomplete preference list
  - Sublinear Complexity

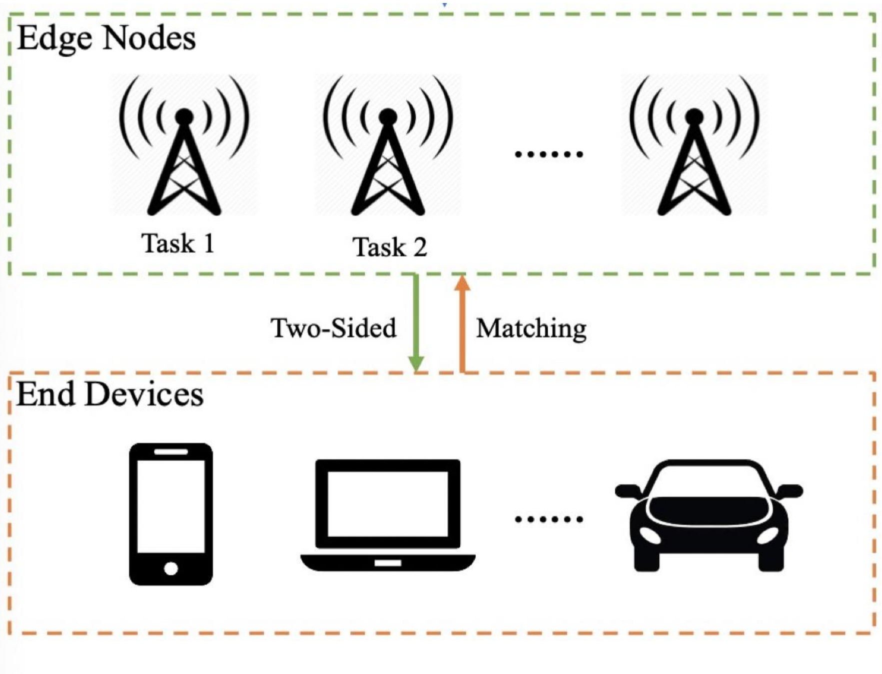


Fig. 2. The multi-task federated learning framework in MEC scenario.

Dawei Chen, Choong Seon Hong, Li Wang, Yiyong Zha, Yunfei Zhang, Xin Liu and Zhu Han, ``Matching Theory Based Low-Latency Scheme for Multi-Task Federated Learning in MEC Networks," IEEE Transactions on Mobile Computing, 2021.

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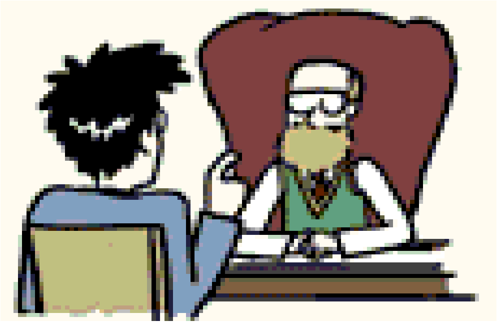
Contract Theory

- How to regulate monopoly with *asymmetric information* by introducing cooperation among competitors. Jean Tirole - Nobel Prize 2014, 2016
- Before Contract: Adverse Selection for Ph.D. Students

- The plan you try to find the advisor with financial aid



- "I am going to be a professor at a major research university after I graduate."

- The real plan

- Look for career alternatives

- The secret plan

- Become a baker/rock star/writer

Solution: Two contracts
- One for theory
- One for practice
- Truthfully revelation

Contract Theory

After Contract: Moral Hazard for Ph.D. Students

- What my parents thinks I do

- What my advisor thinks I do

What I actually do

- When advisor presents

- When advisor on travel

Solution:

- Align student's & professor's interests

Example 1: 3 years playing and 1 year fighting with professor

- Difference between 4 year

3 paper graduation policy and 3 paper graduation policy

Example 2: Publish in rubbish places

- Stronger than marriage

Advisor/student relationship

- Future employer will check where published to judge student's Intellectual ability

Block Chain and Cryptoeconomics

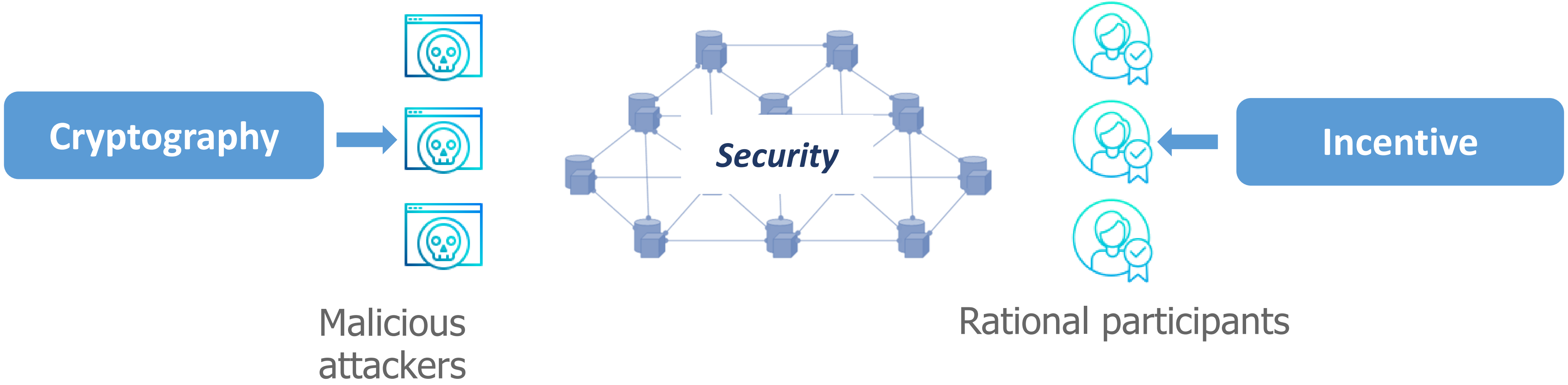
- ❑ What is the relation between Blockchain and Cryptoeconomics?

> Blockchain projects and the blockchain-based solutions are the ***instances of cryptoeconomics***.

  - Bitcoin, Ethereum;
  - Proof of Work, Proof of Stake;
  - State Channels, Plasma, Sharding, Roll-up solutions.

- ❑ What is Cryptoeconomics?

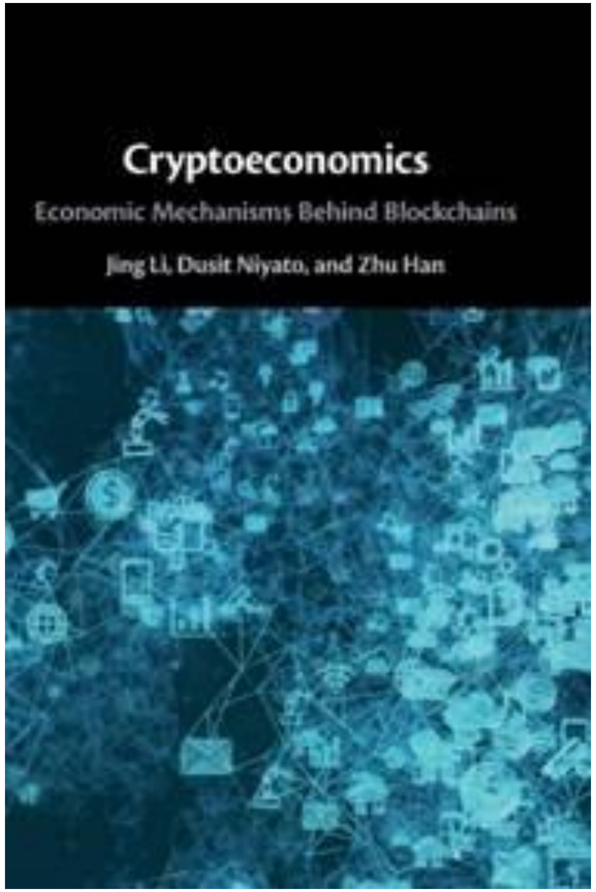
> Cryptoeconomics is the application of incentive mechanism design to information security problems. (Vlad, 2015)



Cryptoeconomics

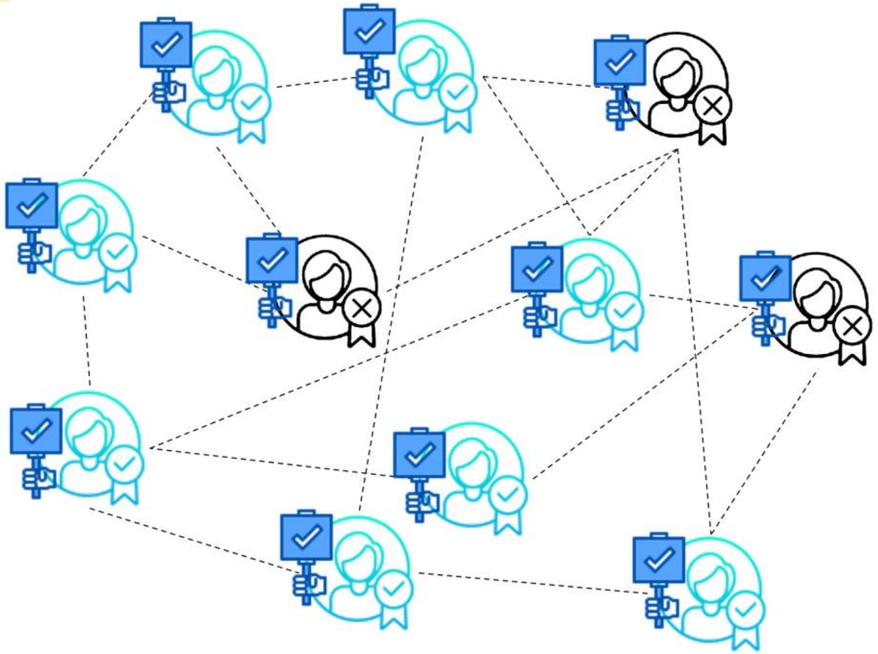
❑ How does the incentives secure a distributed system?

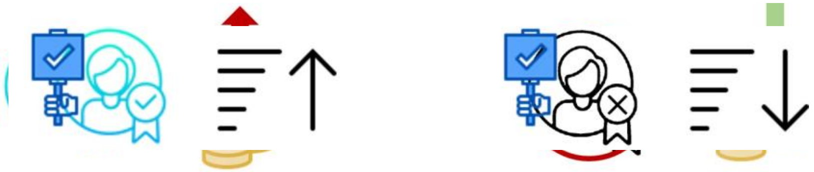
- ***Rewards***: increase actors' token balances if they do something good.
  a) Block reward.
  b) Transaction fee.



- ***Penalties***: reduce actors' token balances if illegal behavior occurs.
  a) Security deposits.

- ***Privileges***: incentivize participants by giving them decision-making right.
  a) Voting weight





Outline

- Introduction
- Resource Allocation in Wireless Networks
- **Assorted Game Theoretical Approaches**
  - Non-Cooperative Game Basics
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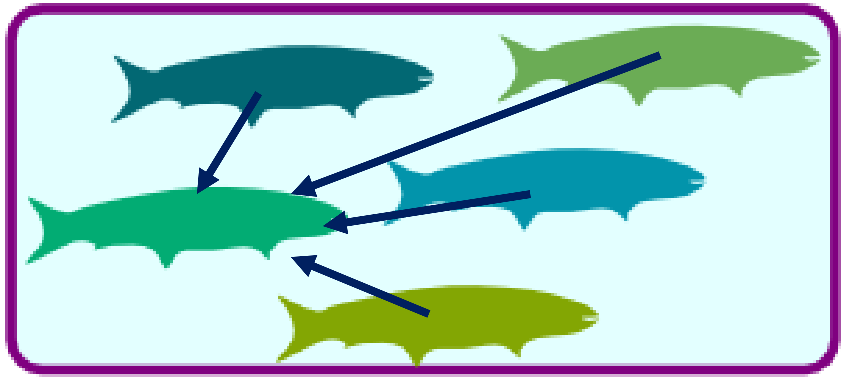
Classical Game Theory vs Mean Field Game

- Classical game theory – models the interaction of a single player with each of the other players



- a fish reacts to what other nearby fishes do

- Mean field game – models the interaction of a single (reference) player with the collective effect of the other players

- a fish reacts only to the mass of fish nearby

Mean Field Games

- Mean field games (MFGs) study the existence of Nash equilibria in games involving a large number of asymptotically negligible players modeled by controlled stochastic dynamical systems.
- MFGs refer to methods and techniques that study differential games with large population of indistinguishable, rational, and heterogeneous agents
  - Indistinguishable – players share common structures of the model
  - Rationality – players act optimally (maximize utility / minimize cost)
  - Heterogeneity – players can have heterogeneous states
- MFGs reduce to a standard control problem and an equilibrium.
- MFG has one step ahead compared with mean solution

Mean Field Game v.s. Others

Optimization Problem

$$\underset{u \in \mathcal{U}}{\text{minimize}} \quad J(u)$$

Game Theory

$$\underset{u_i \in \mathcal{U}_i}{\text{minimize}} \quad J_i(u_i, \mathbf{u}_{-i})$$

Optimal Control Problem

$$\begin{aligned} &\underset{u \in \mathcal{U}}{\text{minimize}} && J(u) \\ &\text{subject to} && \dot{x} = f(t, x, u) \end{aligned}$$

Differential Game

$$\begin{aligned} &\underset{u_i \in \mathcal{U}_i}{\text{minimize}} && J_i(u_i, \mathbf{u}_{-i}) \\ &\text{subject to} && \dot{x} = f(t, x, u_i, \mathbf{u}_{-i}) \end{aligned}$$

Mean Field Game

$$\begin{aligned} &\underset{u \in \mathcal{U}}{\text{minimize}} && J(u, m) \\ &\text{subject to} && \dot{x} = f(t, x, u) \end{aligned}$$

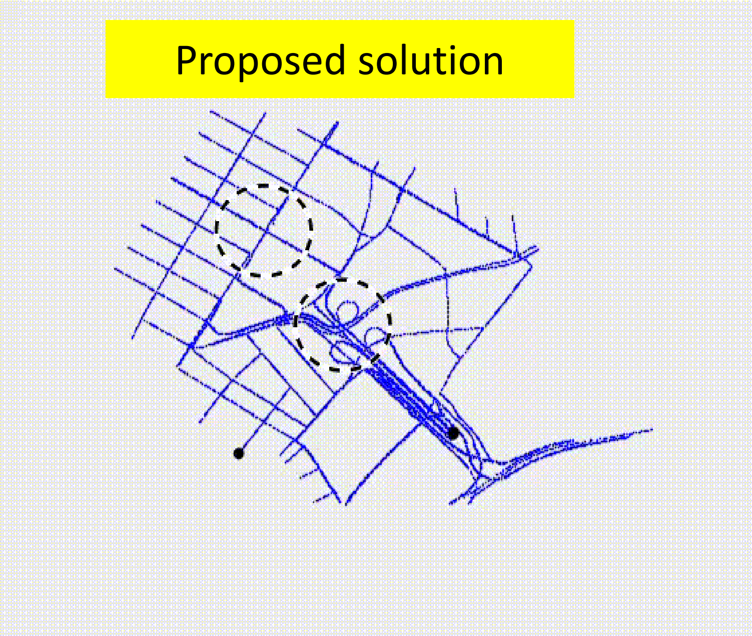
J = **cost function**
x = **state variable**
u = **control**
m = **mean field**

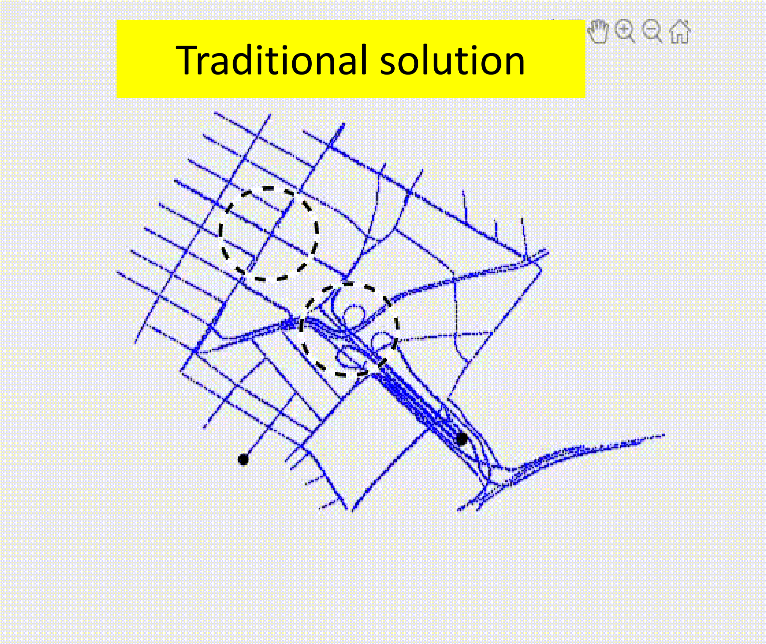
MFG for Edge Computing Fast Offloading

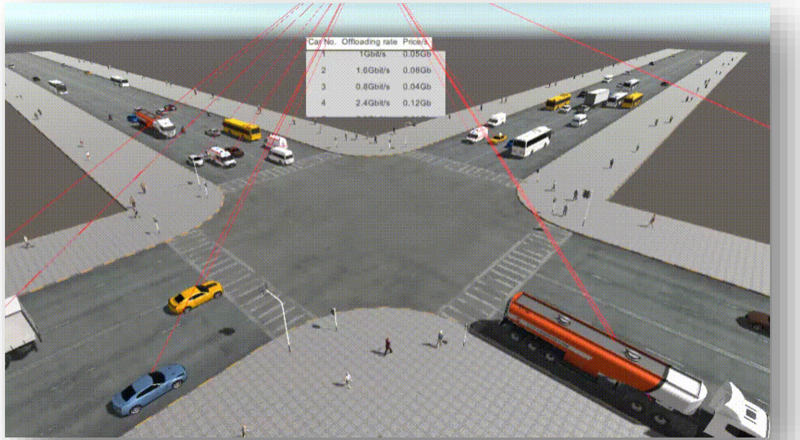
- Industrial Impacts: Brooklyn Bridge Traffic Data: Toyota
- A lot of patents

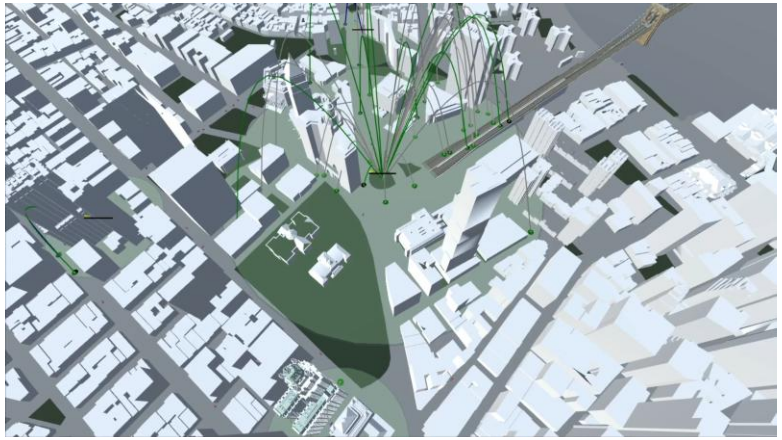
Edge server coverage area

- ● Vehicle
- ● Vehicle meets the latency requirement
- ● Vehicle can't meet the latency requirement









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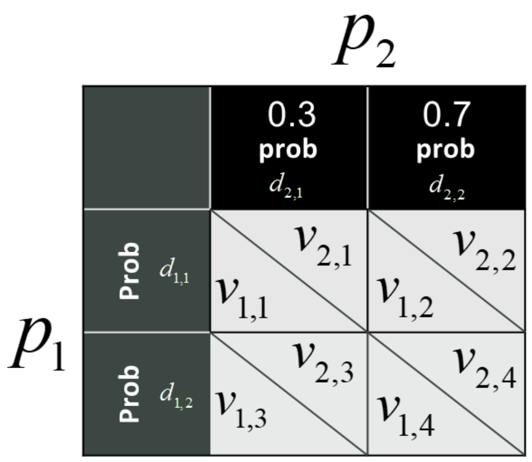
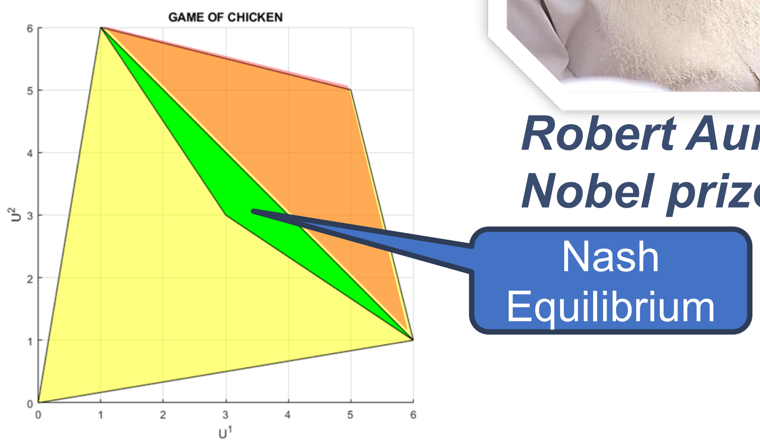
Game Theory and Machine Learning

Goal: Study the correlated equilibrium outside the convex hull of mixed strategy



Robert Aumann
Nobel prize 2005



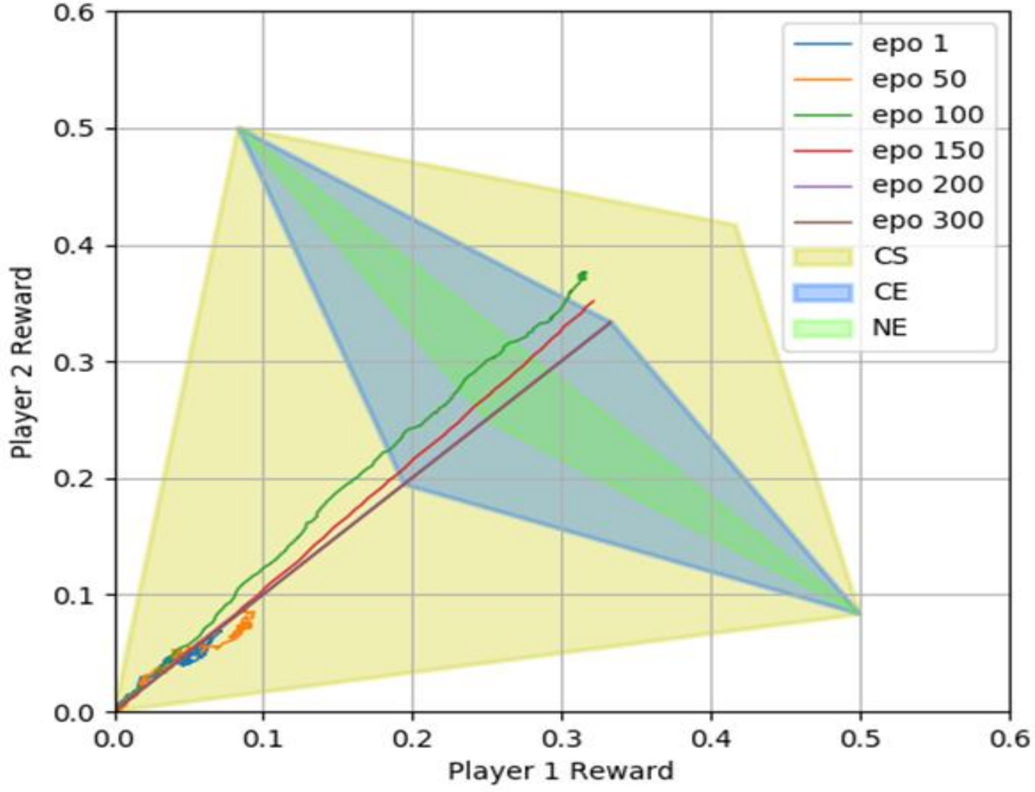
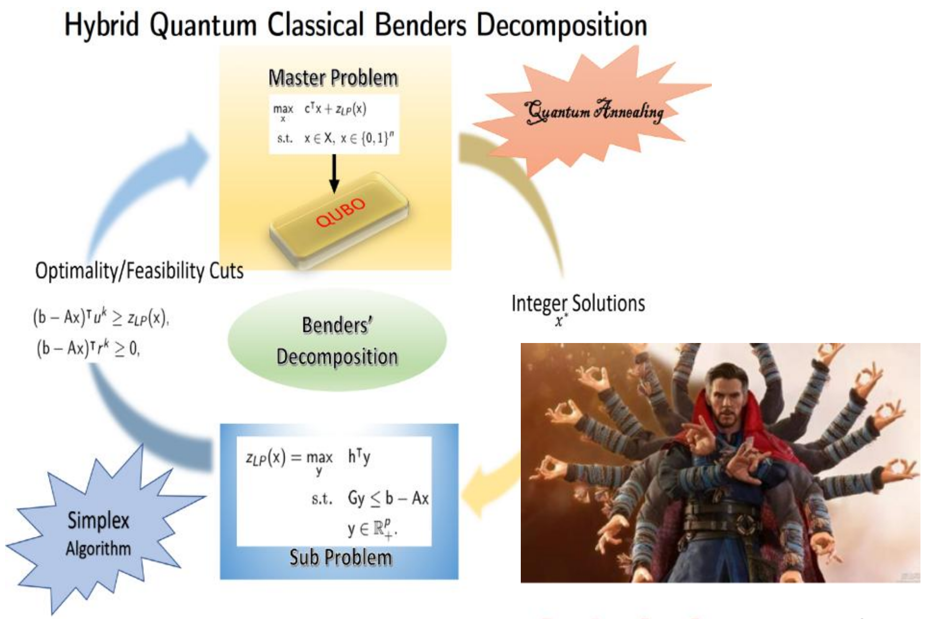


Fig 4: Tracks of Both Players

Recent work to link GAI, LLM, diffusion model with game theory

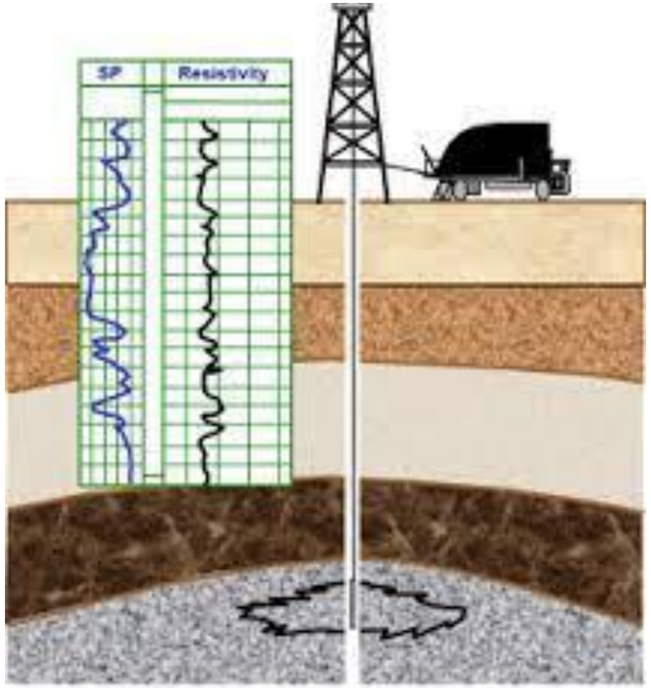
Other Researches in Our Lab



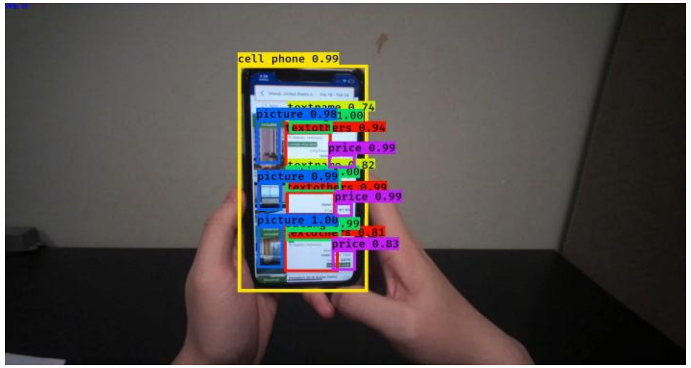
NASA: wireless charging sensor networks and digital twin

Environmental monitoring (Chevron, Shell, and BP)

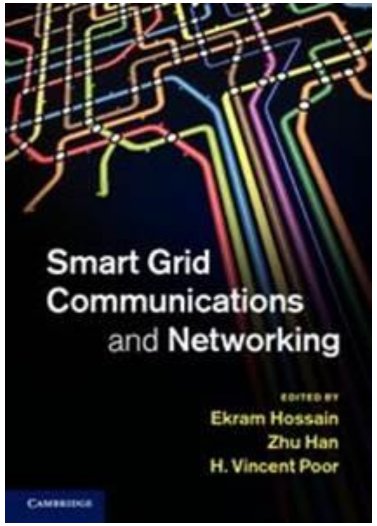
Well Logging



Understanding Consumers Attention on Online Advertisements: An Ambulatory Eye-Tracking Study with Machine Learning Techniques, Amazon Research Awards, 2021,



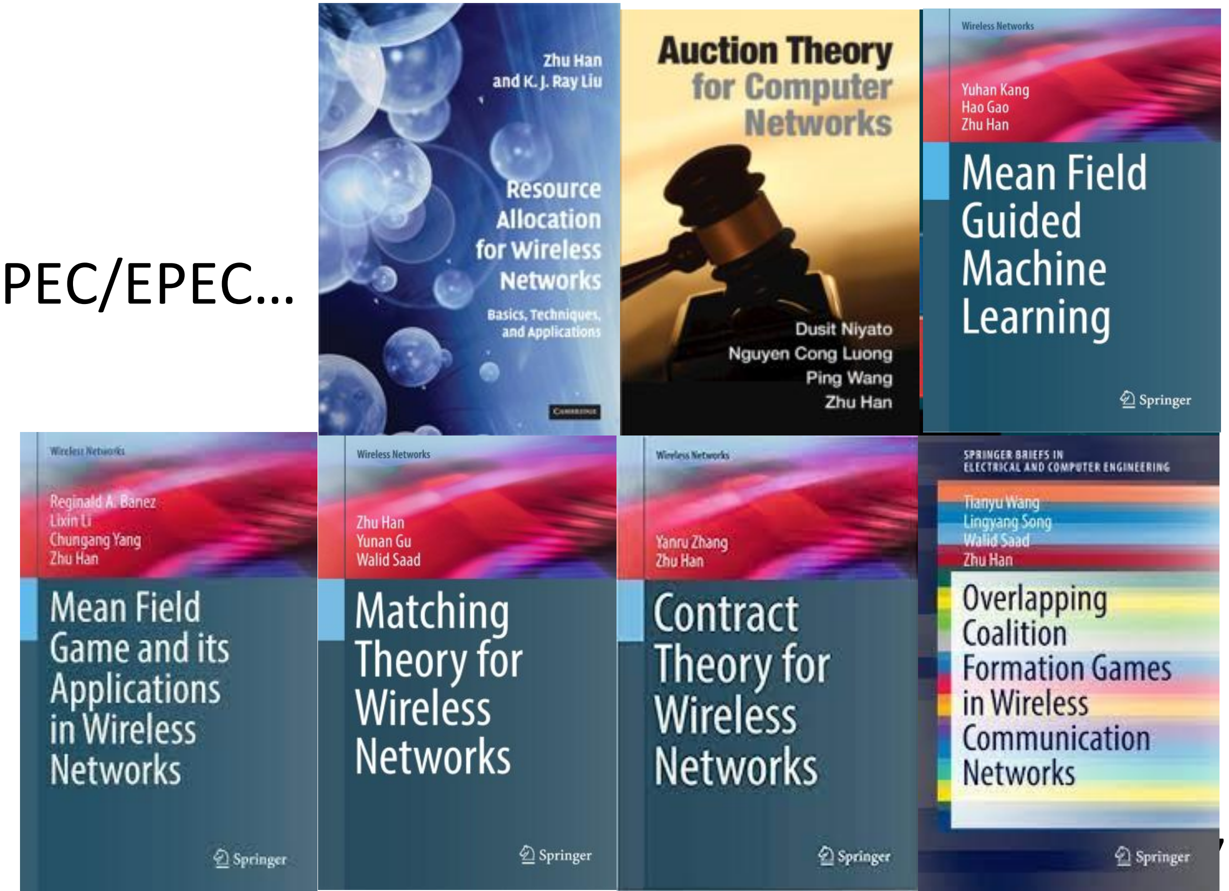
Smart Grid



Conclusions

- ❑ Resource Allocation for 5G, 6G and beyond
  - ❑ Important component to make the system efficient
  - ❑ Centralized vs. distributed solutions
  - ❑ Improved game theoretical approaches over the price of anarchy
- ❑ Assorted Game Approaches
  - ❑ Noncooperative vs. cooperative
  - ❑ Static vs. dynamic
  - ❑ Auction, Contract theory, Matching, MPEC/EPEC…
  - ❑ Joint with machine learning
  - ❑ …
- ❑ Other works

https://wireless.egr.uh.edu/research/



Thanks for Visitors & Group Members

Lab Website: http://wireless.egr.uh.edu/
Personal Website: http://www2.egr.uh.edu/~zhan2/