# *Cross-Layer Design for Spectrum- and Energy-Efficient Wireless Networks*


**Guowang Miao**
**miao@FreeLinguist.com**

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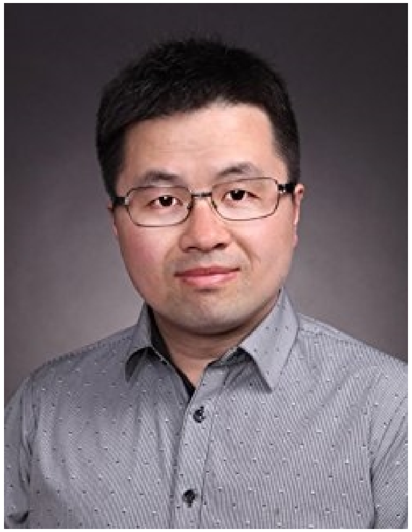
# Presenter Introduction



- Founder of FreeLinguist®, a cloud platform for you to connect with native linguists for quality language services, such as translation, editing, or writing services.
- Expert in communications and networking
- Well known for his original contributions in building a set of fundamental energy-efficient communications theories, which are widely accepted nowadays.
- Inventor of energy-efficient scheduling and capacity-approaching transmission (United States Patent 7782829).
- Author of the graduate textbook entitled Fundamentals of Mobile Data Networks (Cambridge University Press)
- Author of the book entitled Energy and Spectrum Efficient Wireless Network Design (Cambridge University Press).
- Fruitful inventor with many granted patents, some of which have been adopted as essential in 4G standards.

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# Outline

- Introduction
- Wireless Channel Properties
- Basic Concepts
- Spectrum Efficient Design
- Energy Efficient Design
- Energy-Efficient Mobile Access Networks: A Tradeoff Perspective
- Conclusions and References

# 1. INTRODUCTION

# Ancient Wireless Communications

Invasion or no invasion?

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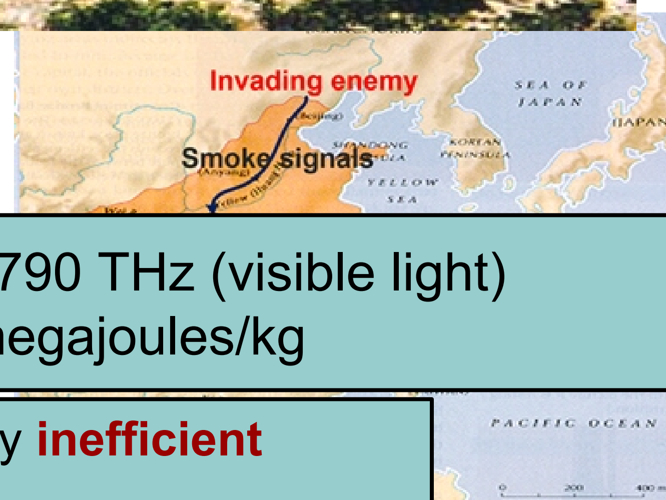


Wireless Communications at 400–790 THz (visible light)
Energy of firewood:16.2 megajoules/kg

Extremely spectrum and energy **inefficient**
**Yet NEEDED**

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# Growing Need of Energy-Efficient Design in Mobile Broadband Access Networks

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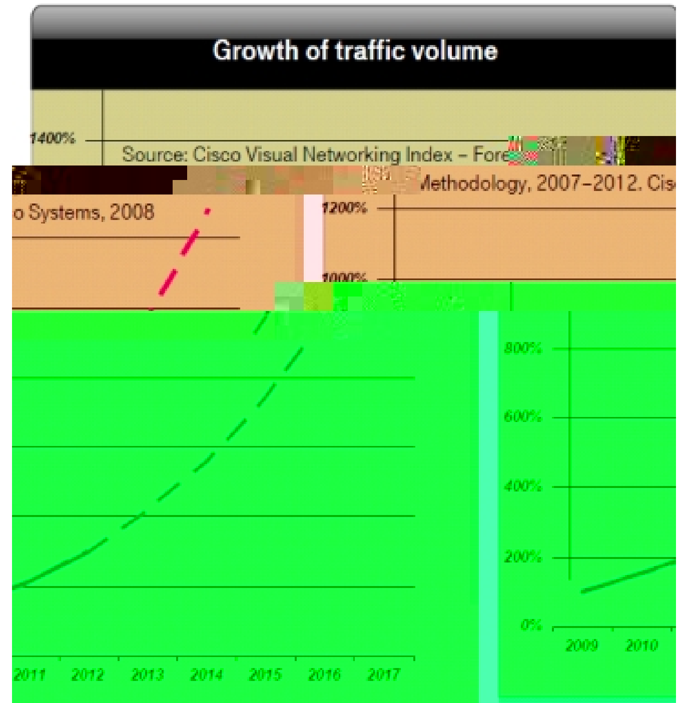

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# Growing Need of Energy-Efficient Design in Mobile Broadband Access Networks

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# Need of Energy Efficiency in Mobile Devices

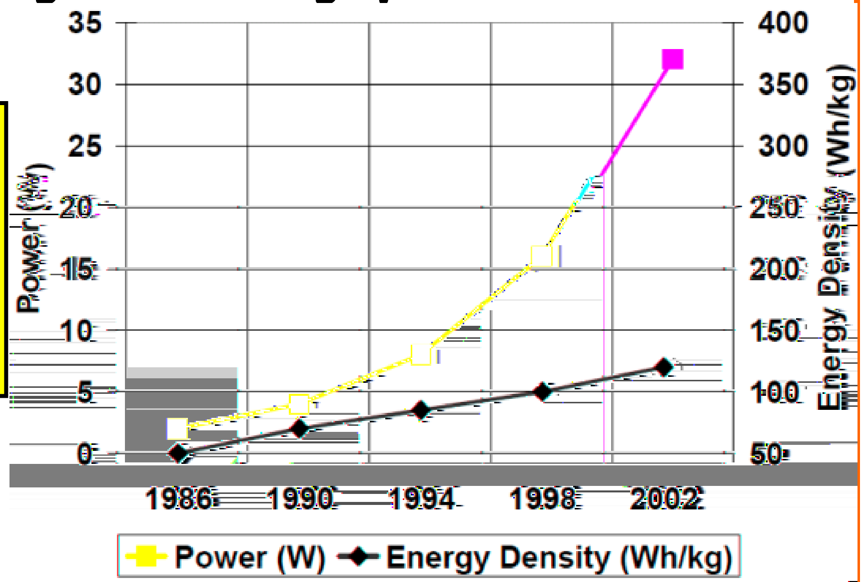
- **Mobile devices are usually battery powered**

Growing demand of mobile traffic

Exponential growth of battery consumption (**150% every two years**)

Slow development of battery (**10% every two years**)

**an exponentially increasing gap between the energy demand and supply**



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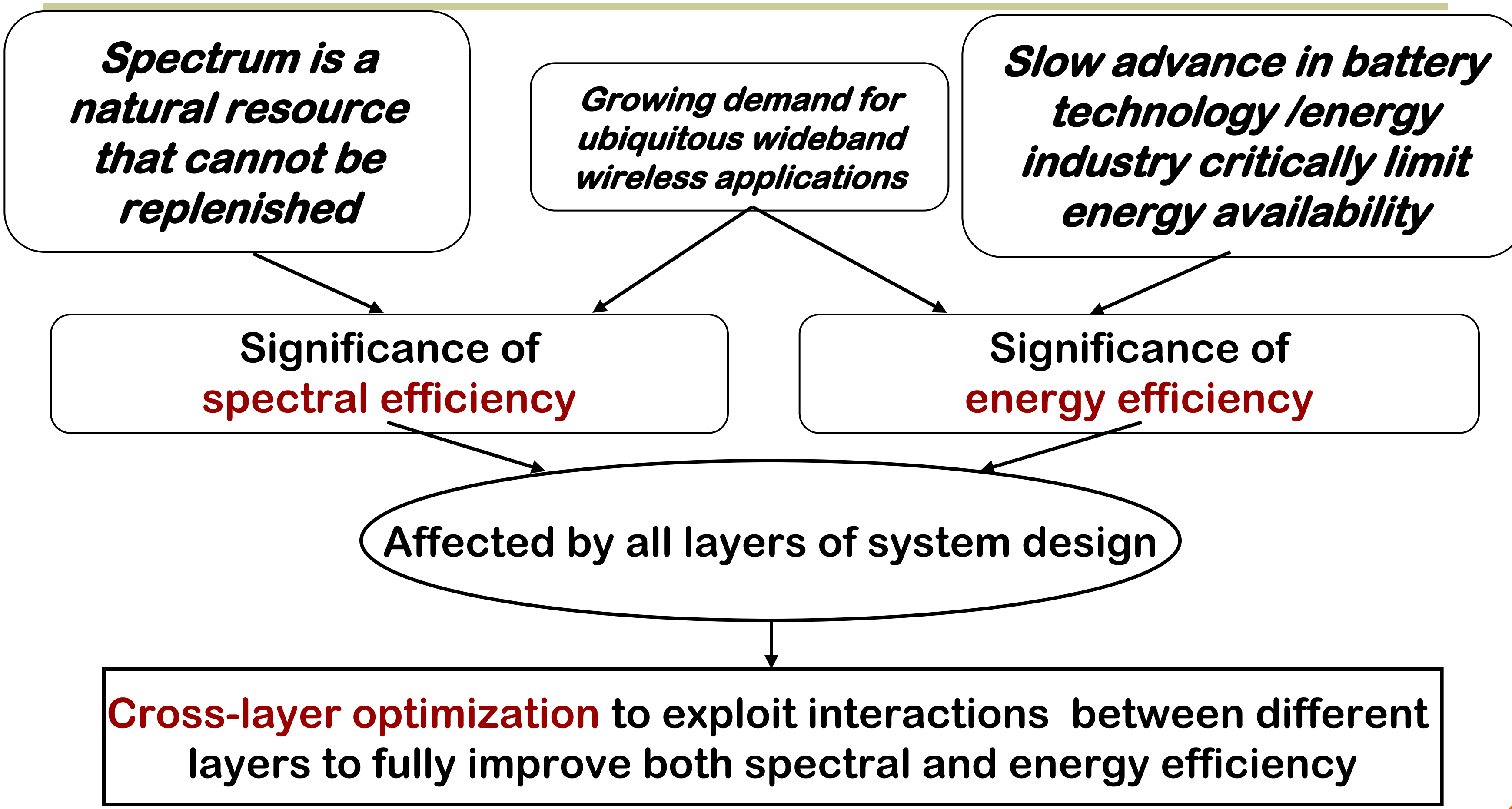
# Critical Demand of SE and EE



# Motivation for Cross-Layer Design

- Traditional Open System Interconnection (OSI) model
  - Divide communication systems into layers
- Cons of separate design
  - Information lost between layers
- Necessity of cross-layer design, especially for wireless communications

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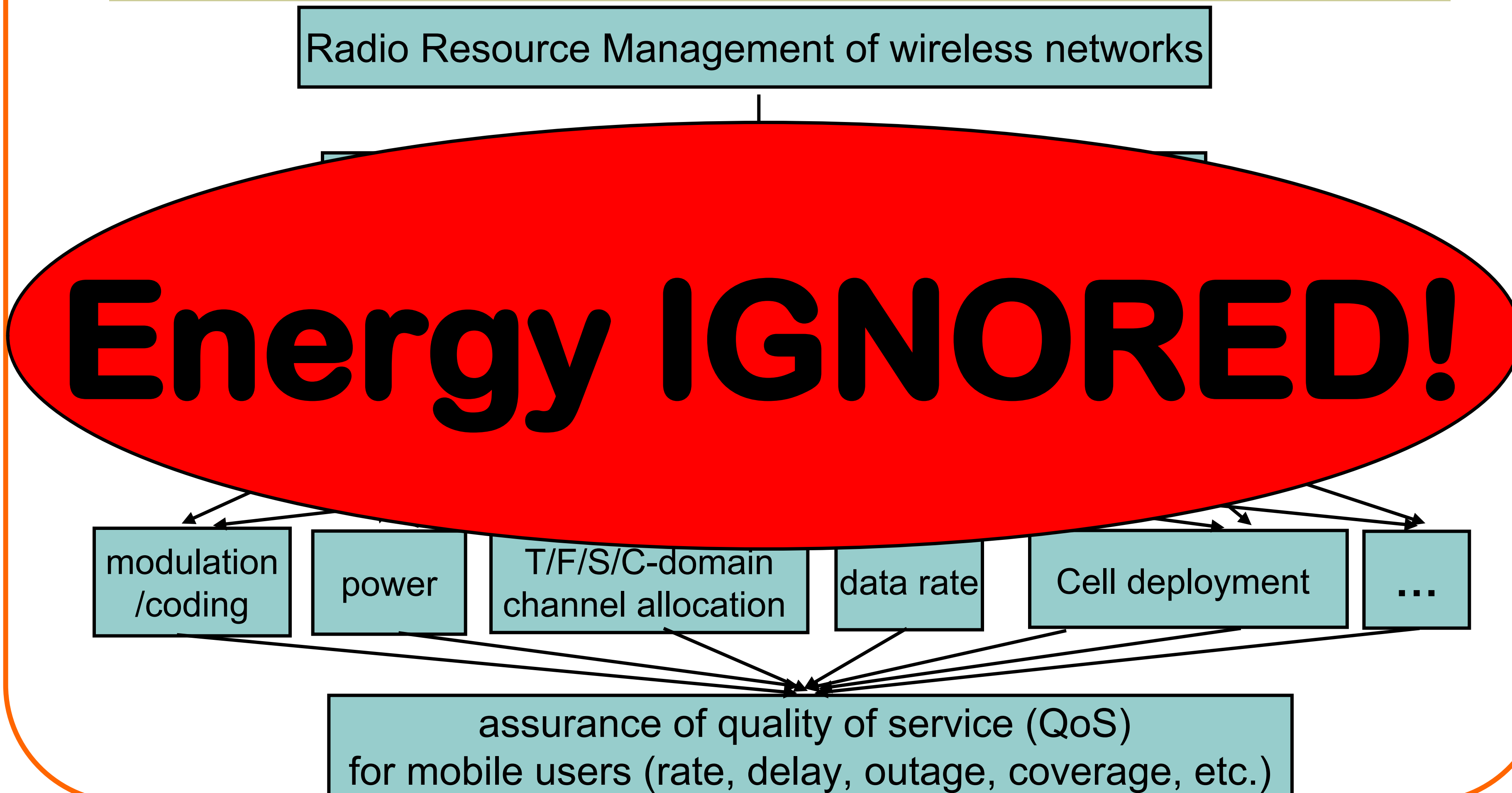
# Revolutionary Thinking Needed



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# Revolutionary Thinking Needed

modulation /coding

…

for mobile users (rate, delay, outage, coverage, etc.)

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# 2. WIRELESS CHANNEL PROPERTIES

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# Propagation and Mobility

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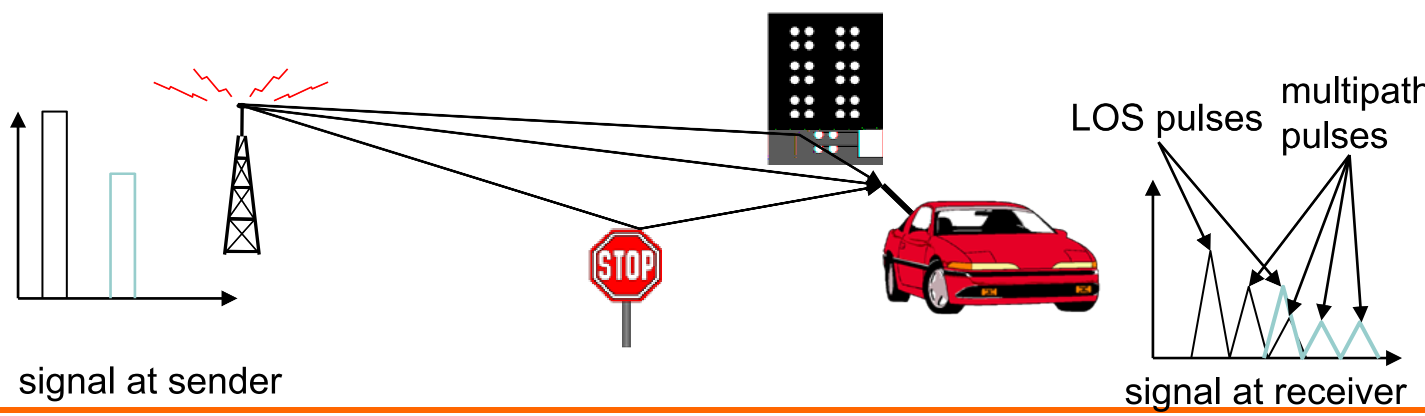
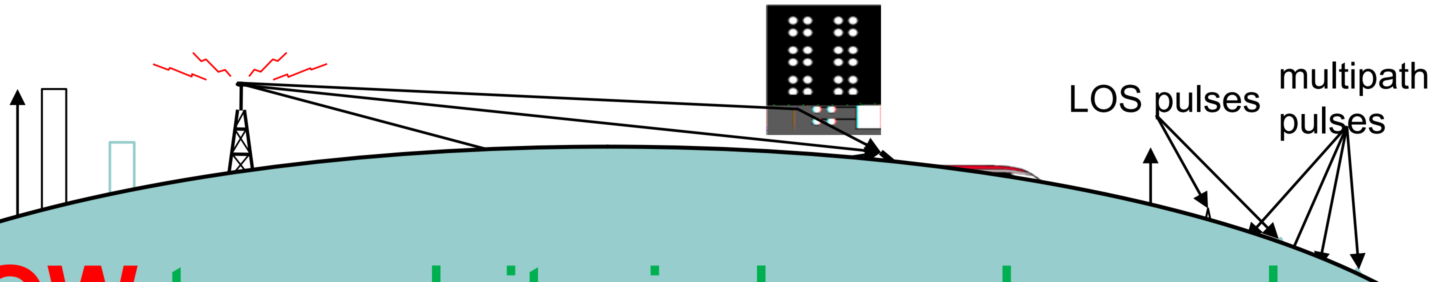


# Fundamental Problem I




**HOW** to exploit wireless channel properties to enhance both spectral and energy efficiency for single-link communications **?**

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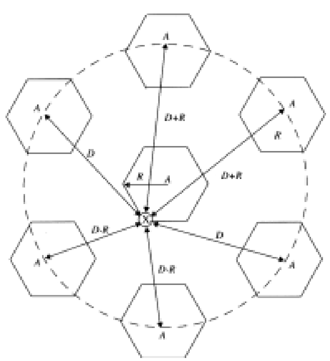
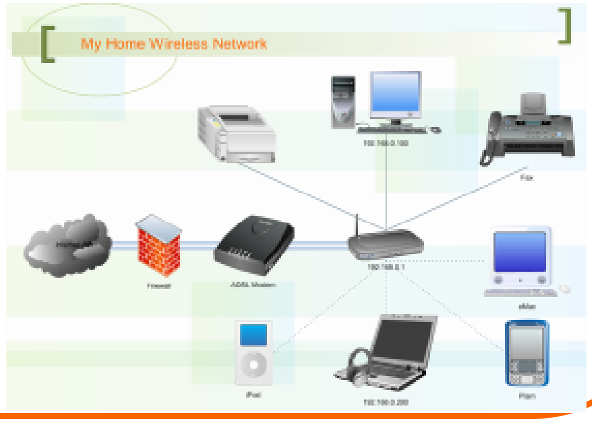
# Multiple User Perspective

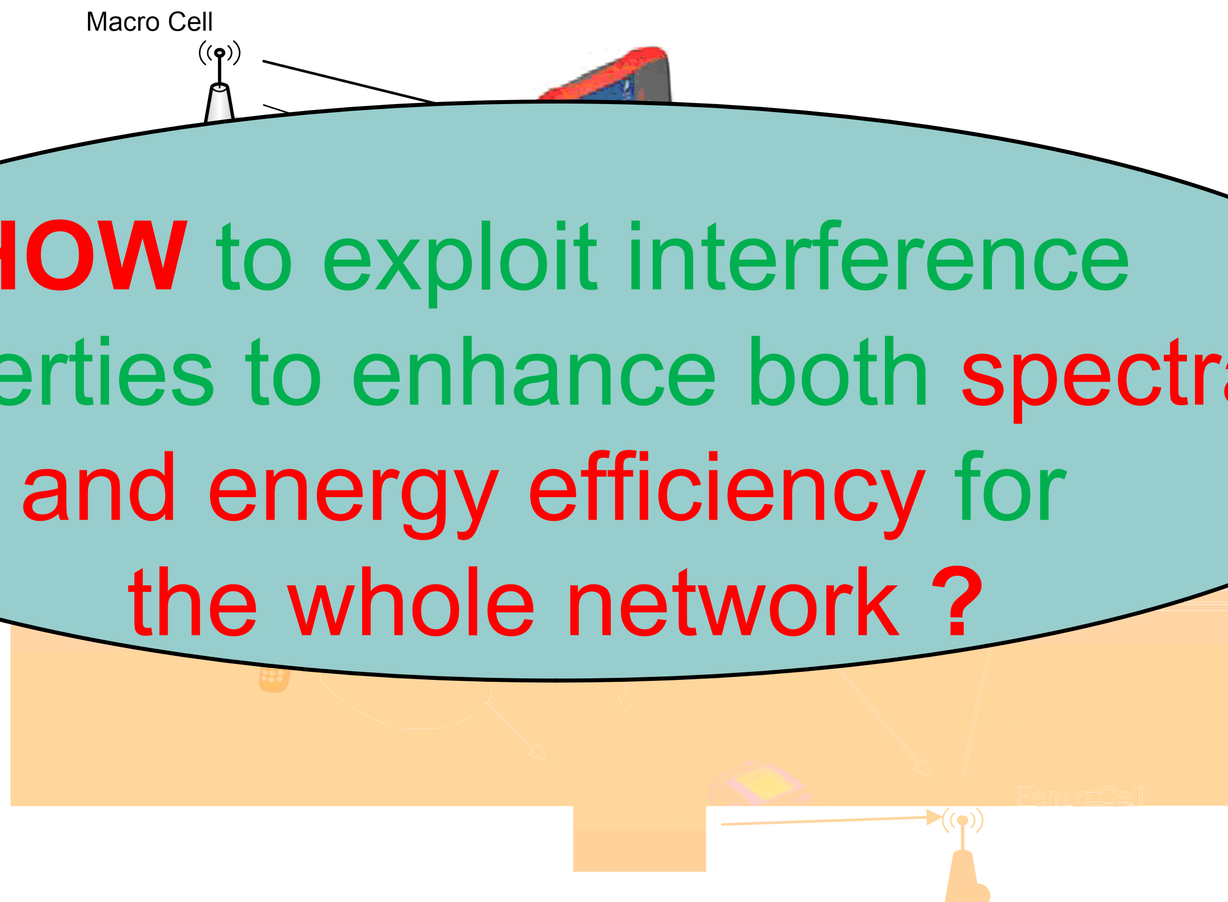
- Wireless channels
  - Broadcast of all signals
  - Due to frequency reuse, different users affect each other through
    - Interference

Forms of Interference





# Fundamental Problem II




**HOW** to exploit interference properties to enhance both spectral and energy efficiency for the whole network ?

# 3. BASIC CONCEPTS

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# Physical Layer

- Physical (PHY) layer
  - Deal with challenging wireless medium
  - Traditionally
    - Operate on a fixed set of operating points
      - Fixed transmit power
      - Fixed modulation and coding scheme (MCS)
    - Pro:
      - Simplicity
    - Con:
      - Channel capacity not fully exploited (low SE)
      - Excessive energy consumption (low EE )
  - Link adaptation: adapt to QoS and environments

# Multi-User Perspective

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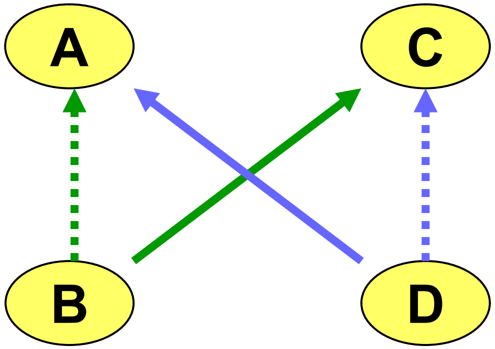
# Wireless Resources

- Non-orthogonal resources
  - Power
    - Users with completely different ( s, t, f, c )
      - Independent communications
    - Two or more users with overlapping ( s, t, f, c )
      - Interact with each other through mutual interference
        - Controlled by **power**
      - Examples:
        - Inter-cell interference in cellular networks (s overlap)
        - Inter-symbol interference (t overlap)
        - Inter-channel interference (f overlap)
    - Energy consumption



# MAC Classification

- MAC determines resource allocation
  - Centralized and distributed MAC
- Centralized MAC
  - Central controller schedules resources of all users
  - Examples: data channels in cellular networks
  - Pros: high performance, easy control of resource assignments …
  - Cons: high complexity, poor scalability …

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# Distributed MAC

- Distributed MAC
  - No central scheduler
  - Individual users decide resources independently
    - Use a certain local medium access policy
  - Examples: Aloha, CSMA/CA, 802.11 DCF
  - Low-complexity, high scalability
  - Protocol design determines how network performs

# Design Rules of Distributed MAC

- Traditional rules of distributed MAC design
  - Removal of Idle State
    - Some users have data to transmit  but decide not to while channel is idle
    - Waste of channel capacity
    - Happen frequently with light network load
  - Removal of Collision State
    - With collision, packet transmission fails
    - Waste of both channel capacity and user energy
    - Happen frequently with high network load

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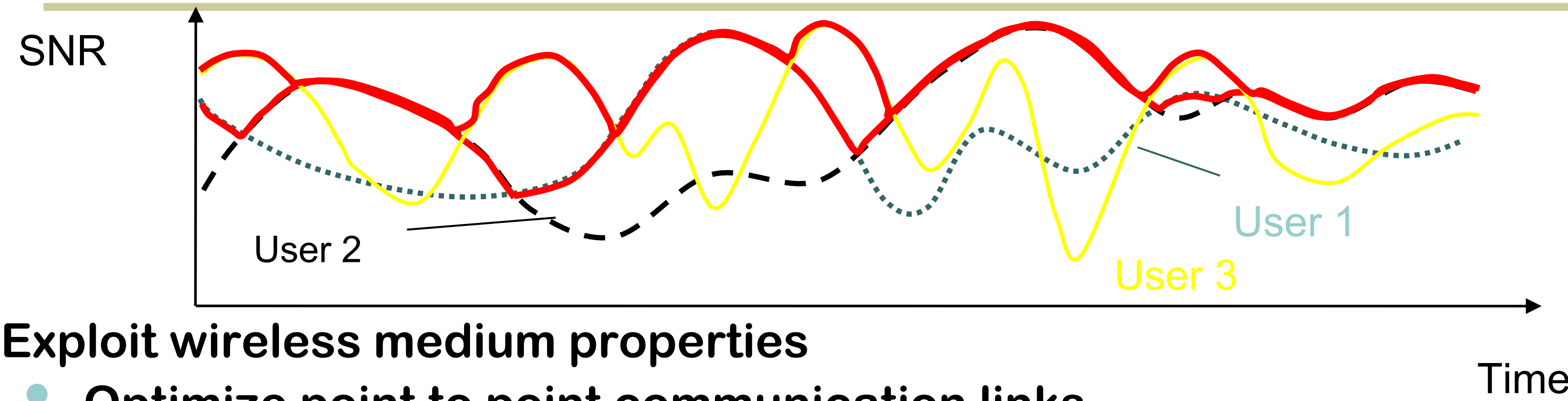
# Focus




- **Exploit wireless medium properties**
  - **Optimize point to point communication links**
  - **Allocate resources to share wireless medium fairly and efficiently**
- **Enhance spectral and energy efficiency through joint optimization of**
  - **Physical layer: power control, adaptive modulation and coding, etc., i.e. link adaptation**
  - **Medium access control (MAC) layer: control the medium access in a distributed or centralized way**

**based on knowledge of channel state information.**

**CSI can be obtained through reciprocity in TDD systems or independent feedback channels.**

# 4. CROSS-LAYER OPTIMIZATION FOR SPECTRAL EFFICIENCY

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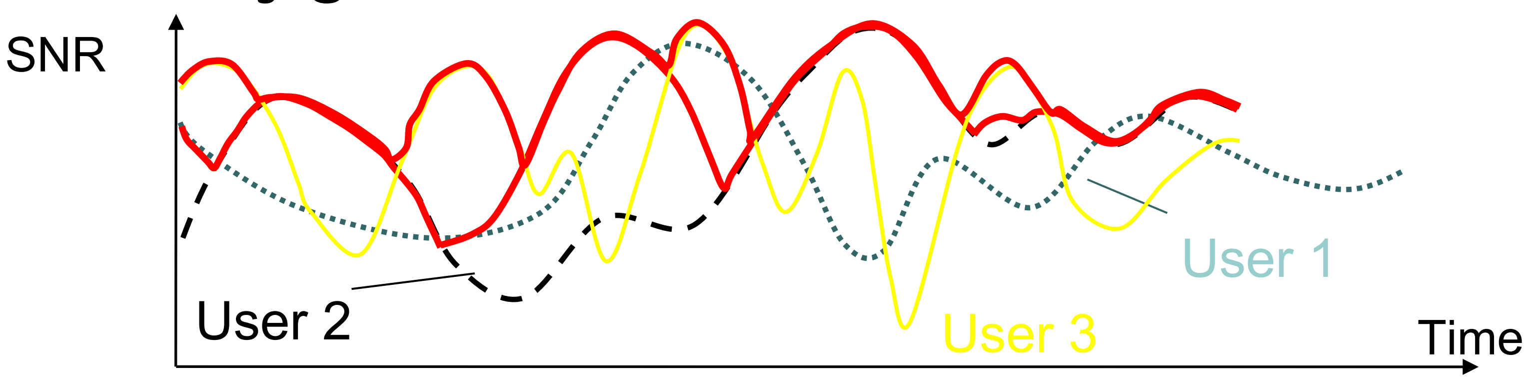
# Multiuser Diversity in A Single Channel System

- **Exploit channel property**
  - Schedule the user with good channel quality
- **Techniques required to exploit multiuser diversity:**
  - Channel state information feedback
  - Adaptive modulation and coding
  - Fast channel-aware packet scheduling
- **Diversity gain increases with the number of users**



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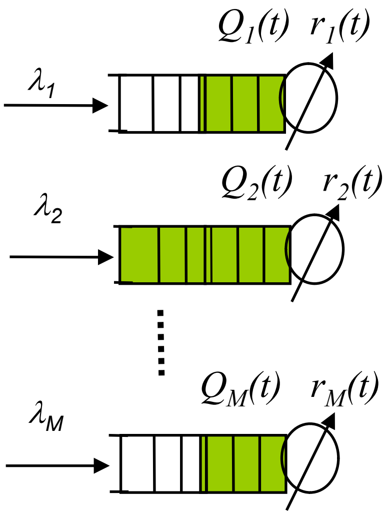
# System Model



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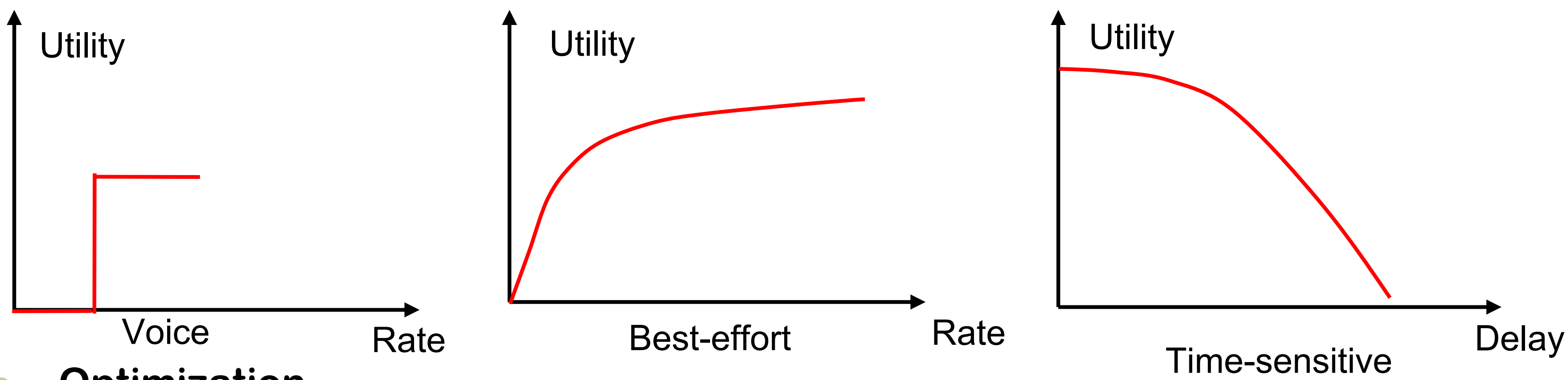
# Cross-Layer Optimization Based on Utility Functions

- **Utility: the level of satisfaction that a user gets from using some resources (economics concept)**
- **Utility functions are determined by applications**




- **Optimization**
  - **Objective: to maximize the sum of utilities in the system**
  - **Subject to: the degrees of freedom of resource allocation**
    - **DSA: Orthogonality of subcarriers**
    - **APA: Maximum total transmit power**
  - **Pros:**
    - **Application-oriented resource allocation**
    - **Flexibility**
    - **Fairness & QoS provisioning**

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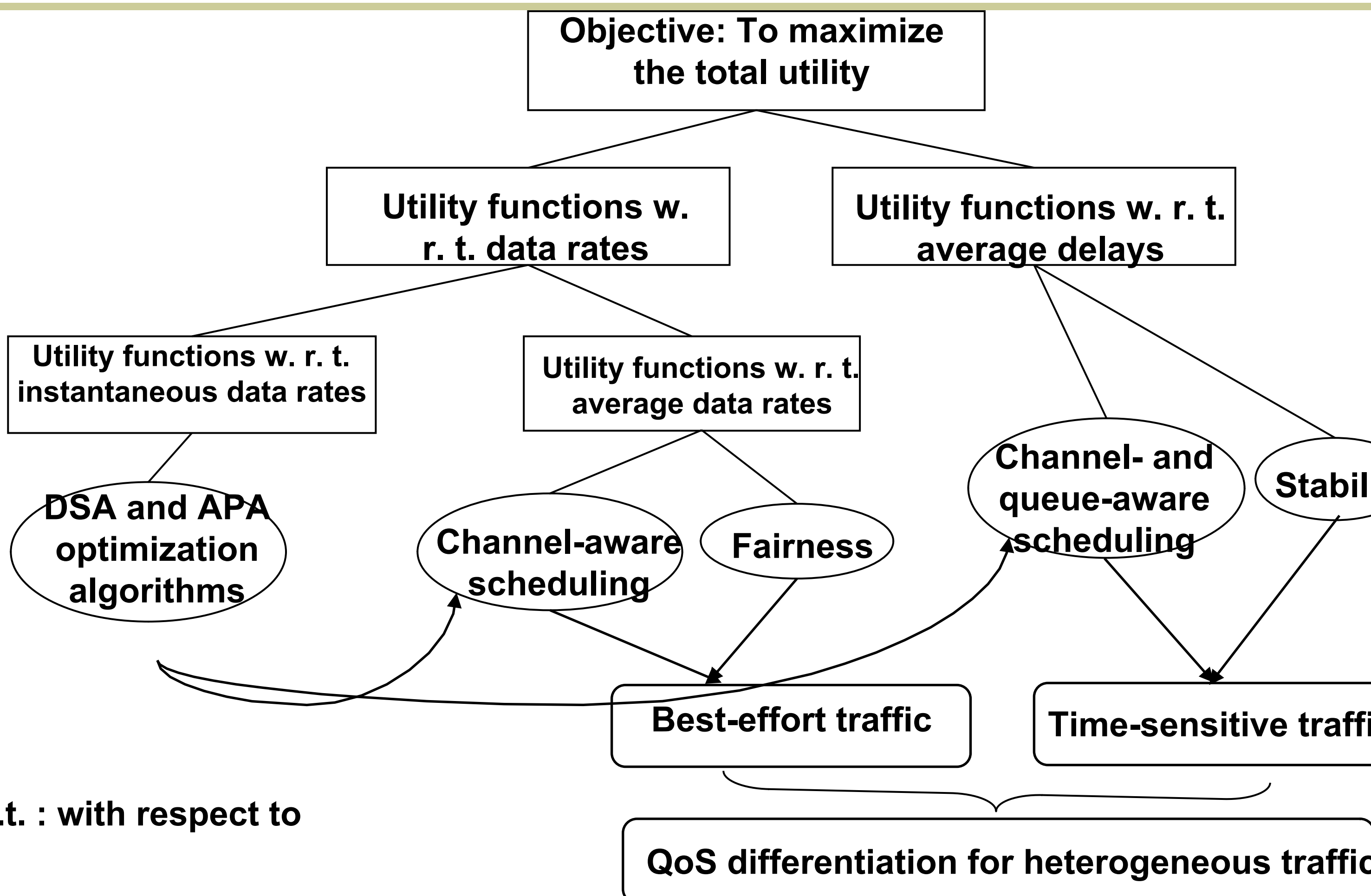
# Scope

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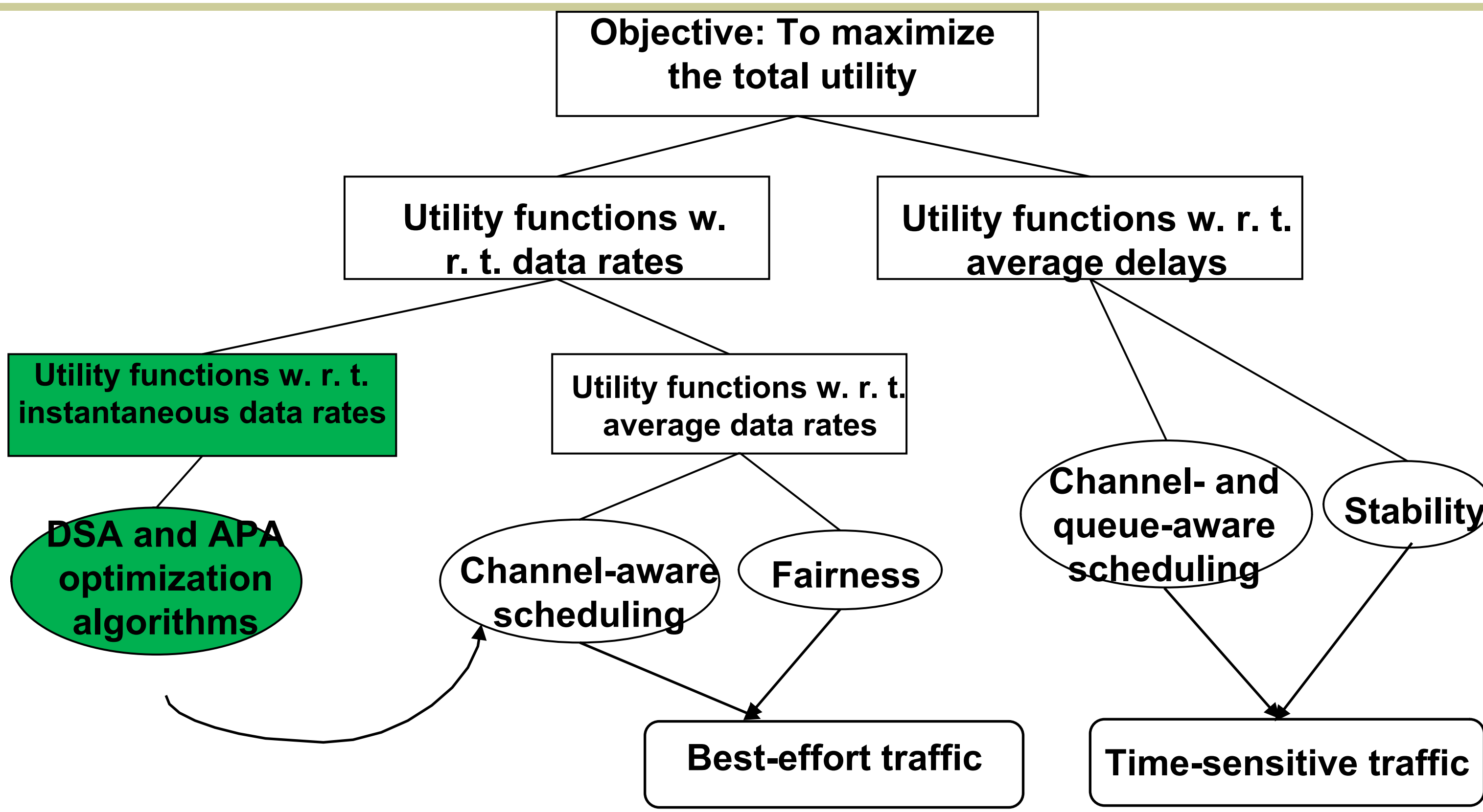
# Scope

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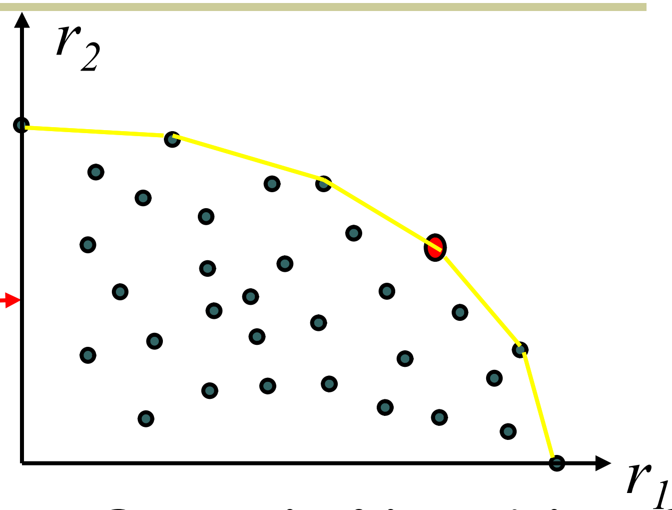
# Utility-Based Dynamic Subcarrier Assignment

$$\max \sum_{i\in\mathcal{M}} U_i(r_i)$$
$$\text{s.t.} \bigcup_{i\in\mathcal{M}} D_i \subseteq \mathcal{K},$$
$$D_i \bigcap D_j = \varnothing, \quad i \neq j \quad \forall i,j \in \mathcal{M},$$
$$p[k]'s \text{ are fixed}$$




- **Nonlinear combinatorial optimization problem with computational complexity $M^K$.**
  - **$M$: the number of users**
  - **$K$: the number of subcarriers**
- **Sorting-Search Algorithm for DSA**
  - **Complexity is about $M^2K\log_2(K)$**
  - **Nearly optimal**

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# Utility-Based Adaptive Power Allocation

$$\begin{aligned} \max \quad & \sum_{i \in \mathcal{M}} U_i(r_i) \\ \text{s.t.} \quad & \sum_{k \in \mathcal{K}} p[k] \leq \bar{P} \\ & p[k] \geq 0, \\ & D_i' s \text{ are fixed} \end{aligned}$$

- **Multi-level water-filling**

$$\begin{cases} p^*[k] = \left[ \dfrac{U_i'(r_i^*)}{\lambda} - \dfrac{1}{\beta \rho_i[k]} \right]^+ & k \in D_i \\ \sum_{k \in \mathcal{K}} p^*[k] = \bar{P} \\ r_i^* = \sum_{k \in D_i} \log_2(1 + \beta p^*[k] \rho_i[k]) \triangle f \end{cases}$$

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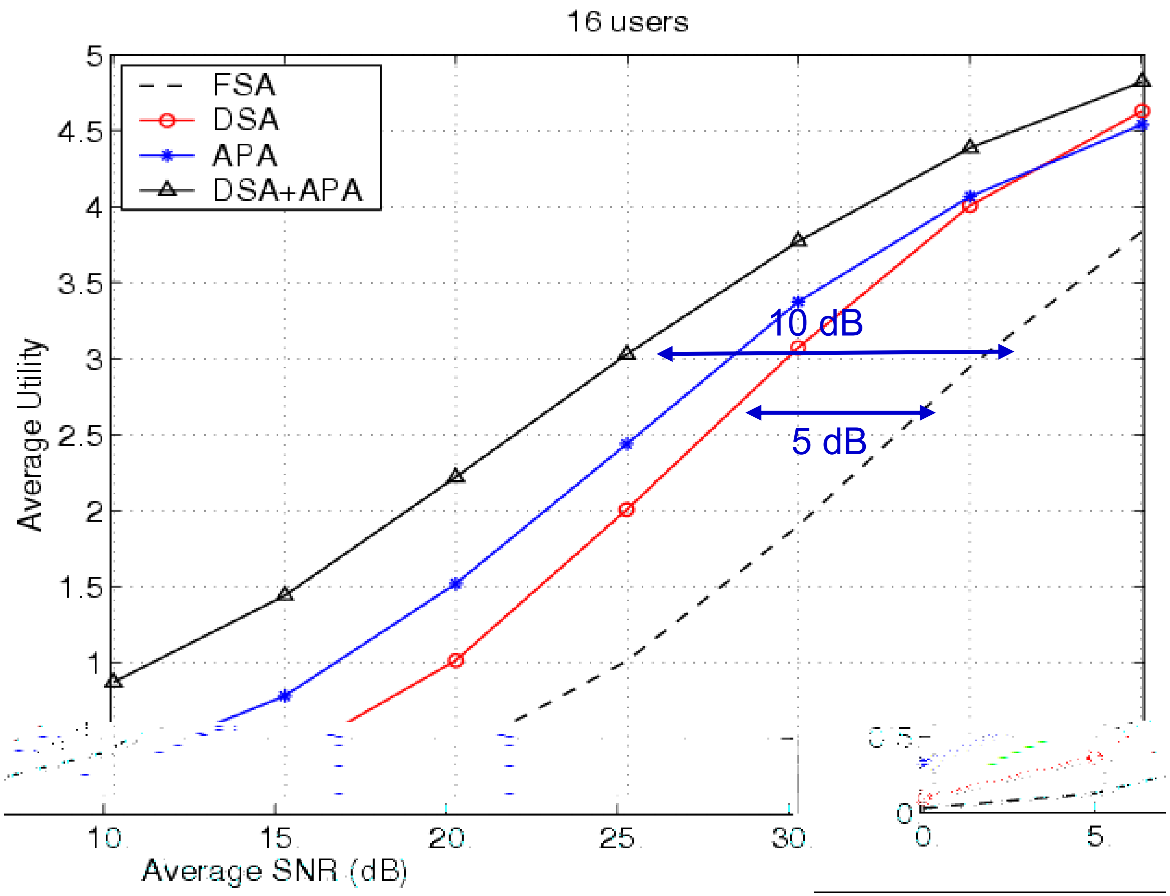
# Simulation Results



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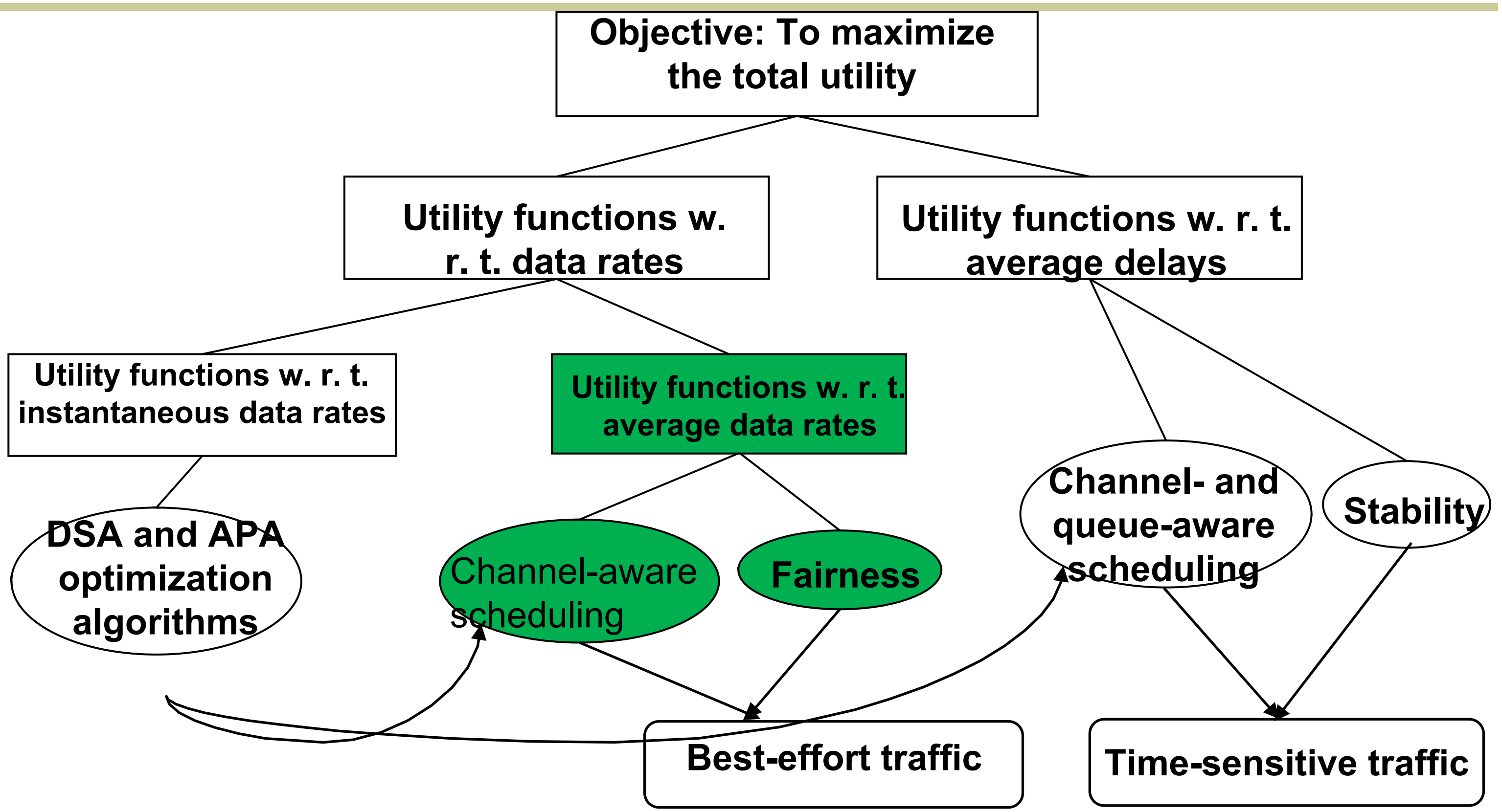
# Scope of Research

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# Channel-Aware Scheduling Using Rate-Based Utility Functions

- **Users care about the average data rate during 1 to 2 seconds, not the instantaneous one.**
  - **Average data rate:** $\bar{r}_i[n] = (1 - \rho_w)\bar{r}_i[n-1] + \rho_w r_i[n]$
  - **Optimization objective:** $\max \sum_{i \in \mathcal{M}} U_i(\bar{r}_i[n])$
- **The solution for DSA is very simple.**

$$\widehat{m}(k,n) = \arg\max_{i \in \mathcal{M}} \{ U_i'\underbrace{(\bar{r}_i[n-1])}_{\text{Priority}} \cdot \underbrace{c_i^{\mathrm{P}}[k,n]}_{\text{Achievable instantaneous rate}} \}$$

- **A utility function is associated with a kind of fairness**

$$\widehat{m}(k,n) = \arg\max_{i \in \mathcal{M}} \{ \frac{1}{\bar{r}_i[n-1]} \cdot c_i^{\mathrm{P}}[k,n] \}$$

- **Multichannel proportional fair scheduling**

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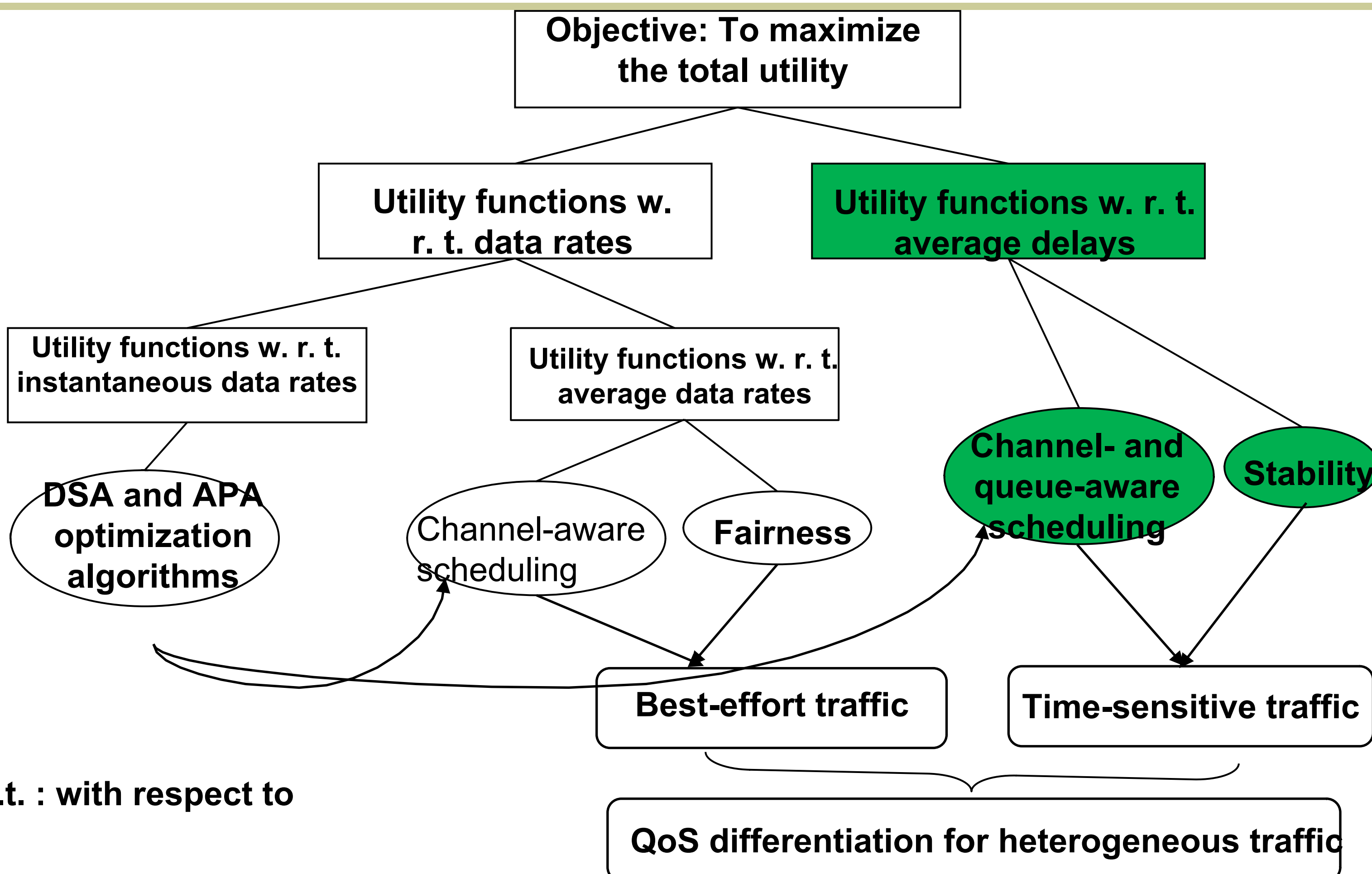
# Scope of Research

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# Max-Delay-Utility (MDU) Scheduling

- **Utility functions w.r.t. average waiting time**
  - **Average waiting time, $W \rightarrow$ Satisfaction level, $U(W)$**
- **Optimization problem of MDU scheduling**
  - **Objective: to maximize the total utility with respect to the predicted average waiting time at each time slot**

$$\max_{D_i^{(n)}, i \in \mathcal{A}^n} \quad \sum_{i \in \mathcal{A}^n} \frac{\left|U_i'(W_i[n])\right|}{\bar{r}_i[n]} \qquad r_i[n]$$

$$\text{subject to} \quad \bigcup_{i \in \mathcal{A}^n} D_i^{(n)} \subseteq \mathcal{K},$$

$$D_i^{(n)} \bigcap D_j^{(n)} = \varnothing, \quad i \neq j \quad \forall i, j \in \mathcal{A}^n,$$

$$r_i[n] \leq \frac{Q_i[n]}{T_s}, \quad i \in \mathcal{A}^n$$

- **Joint channel- and queue-aware scheduling**
  - **Awareness of channel conditions $\rightarrow$ improve network capacity**
  - **Awareness of queue information $\rightarrow$ ensure QoS**

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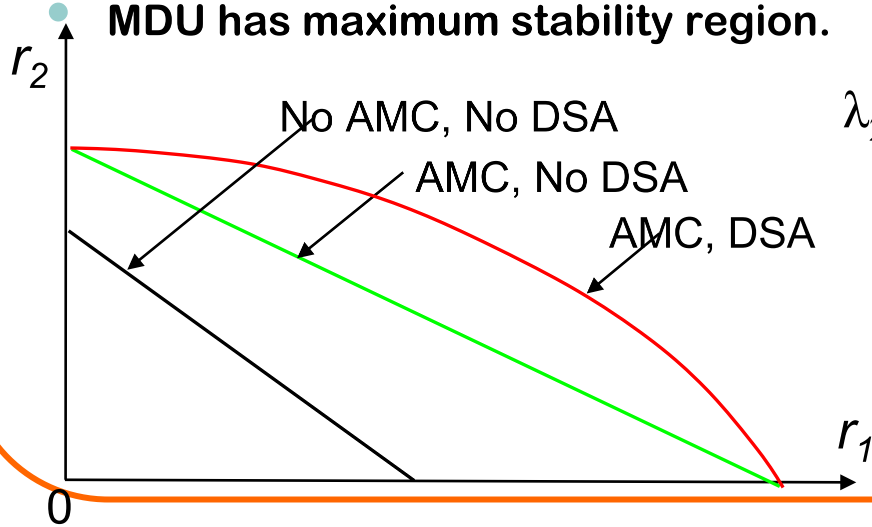
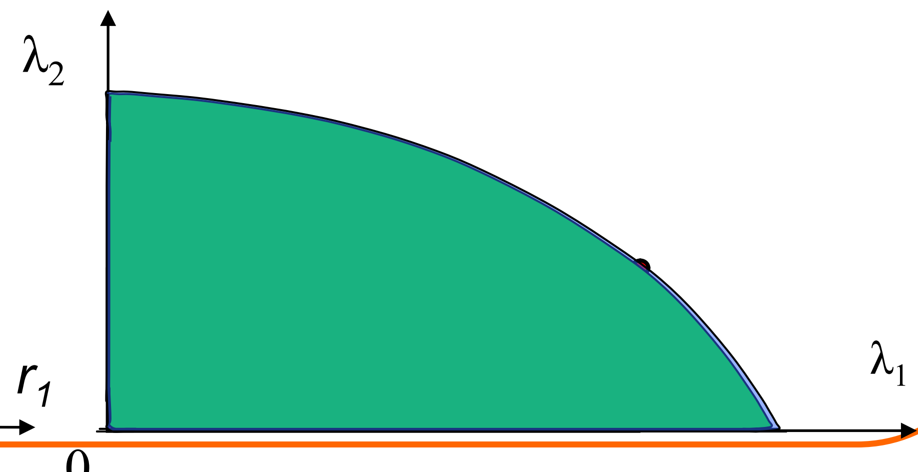
# Stability Region

- **Ergodic capacity region vs. Stability region**
  - **Ergodic capacity region consists of all (long-term) average data rate vectors under all possible resource allocation schemes, given the statistics of the channels**
  - **Stability region of a scheduling policy is defined to be the set of all possible arrival rate vectors for which the system is stable under the policy.**
  - **Stability region $\subset$ Ergodic capacity region**
  - **Maximum stability region: the largest stability region that can be achieved by some scheduling schemes ($\rightarrow$ Ergodic capacity region)**
  - **MDU has maximum stability region.**



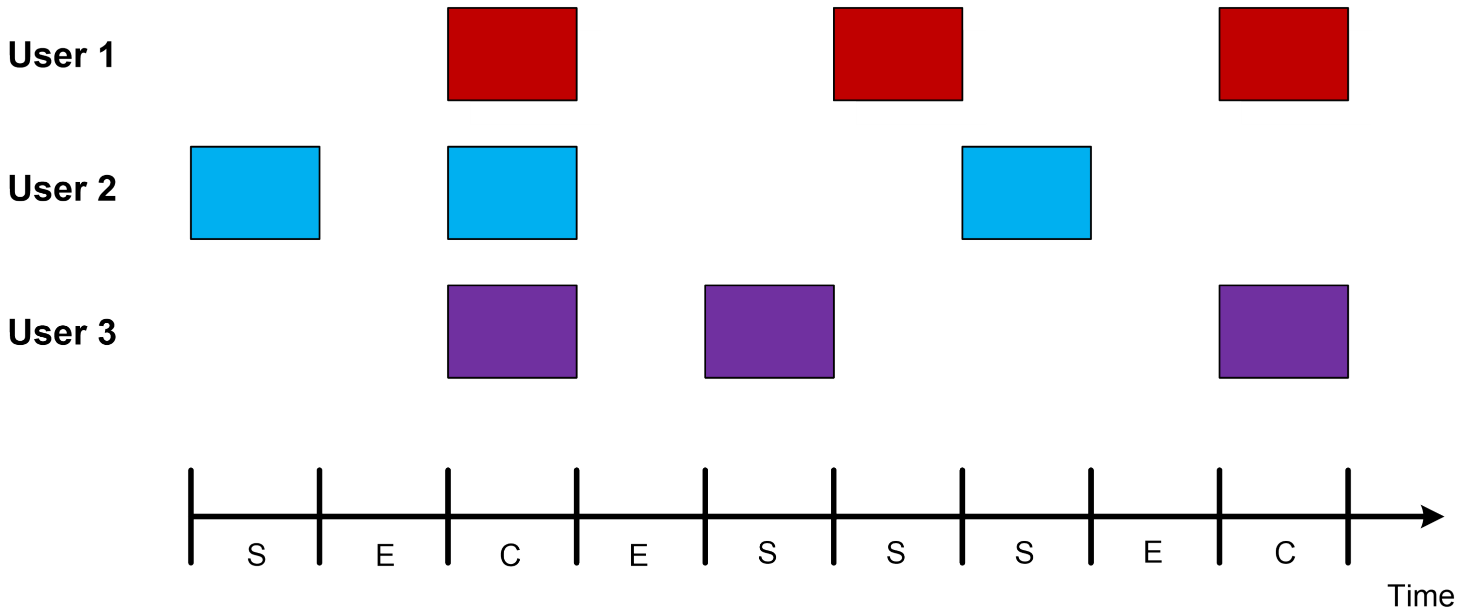



# Recap

- **Centralized Cross-Layer Optimization for SE**
- **Intelligent resource allocation by exploiting channel and queue information**
  -

# Distributed MAC - Traditional Slotted Aloha

- Time divided into slots of equal size
- Users wait until beginning of slot to transmit
- If collision: retransmit with probability p until success.




S: success; E: empty; C: collision

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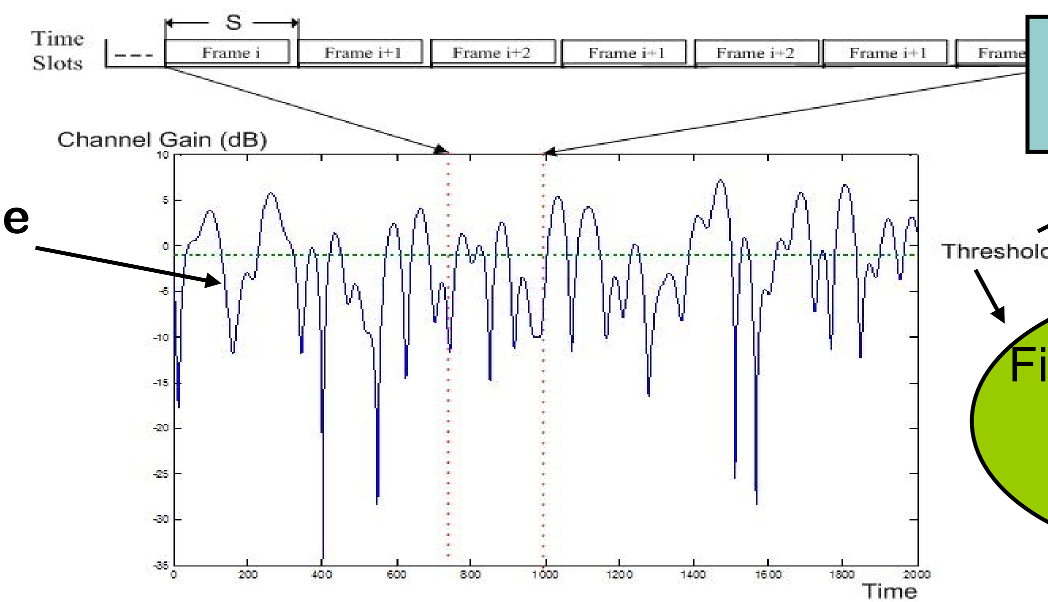
# Access Modeling

- Cons of separate design: 1. transmit a frame when channel is in deep fading; 2. May not transmit  but channel is in good condition
- With cross-layer design
  - Transmit a frame when channel gain is above a threshold
  - Randomize transmission since channel varies randomly

Fading on one subchannel




Control the contention probability

Find optimal values to max network performance

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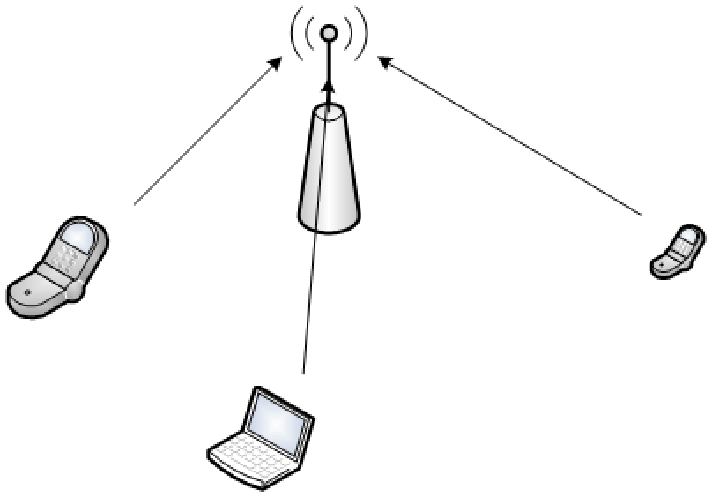
# Opportunistic Random Access – Infrastructure Networks

- Exploits variation inherent in wireless channels to increase network throughput.
- Each user knows its own channel state
- [Qin 03] Each user transmits only if its channel power gain is above a pre-determined threshold that is chosen to maximize the probability of successful transmissions.



# Channel-Aware Aloha

- **N users in the system to send data**
- **Each user knows the distribution of its channel gain**
- **Each user chooses a threshold *Ho* and sends data only if the channel gain is above *Ho* (binary scheduling).**

$$H_o = F^{-1}(1 - \frac{1}{N})$$

Contention probability: 1/N
Asymptotically optimal in N
Asymptotically achieve 1/e of the centralized system's throughput

[YU06]: binary scheduling maximizes the sum-throughput

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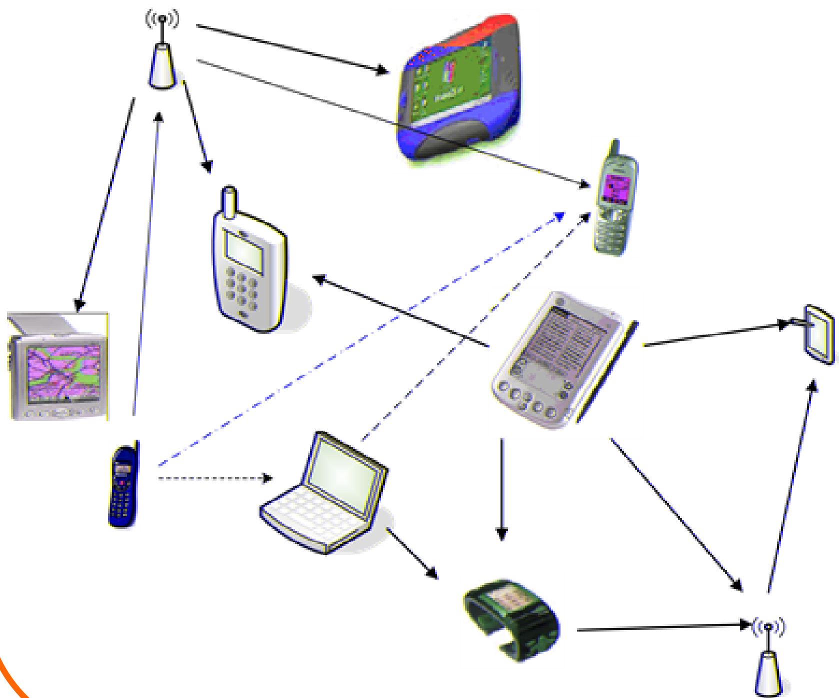
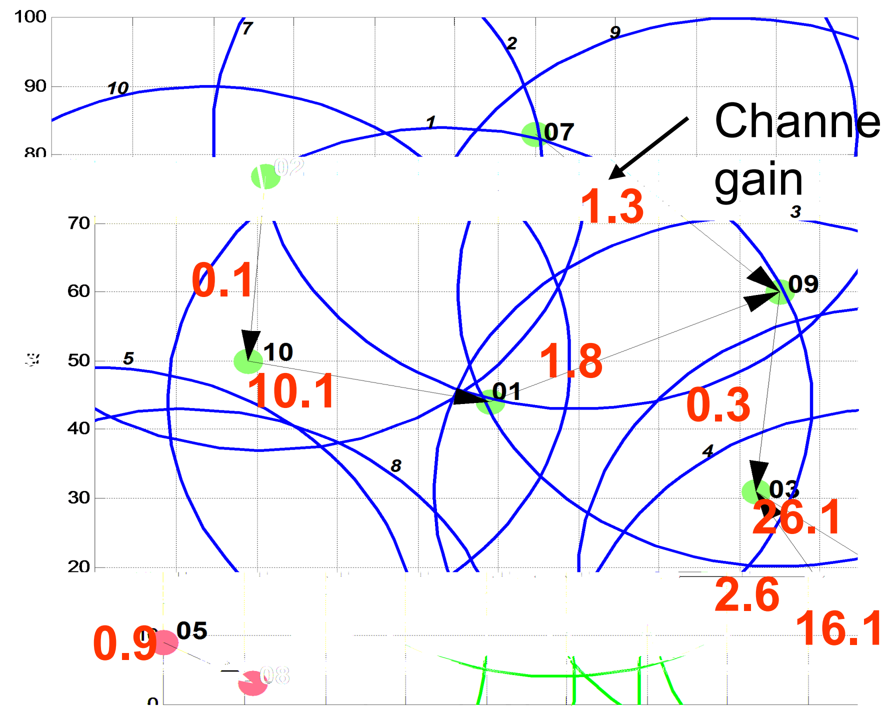
# Opportunistic Random Access – Ad Hoc Networks

- Ubiquitous communications complicate network topology
- No central scheduler for good scalability
- A generic solution





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# Cross-Layer Design Objective

- **Objective:**
  - **Consider both overall network throughput and fairness**
  - **Find optimal threshold configuration and adaptive modulation and coding (AMC)**
- **Cross-layer design criterion**

$$C^* = \arg \max_{\{\text{threshold, AMC}\}} \prod_{\text{active links}} \textbf{link throughput}$$

**subject to**

**average power constraint**

**and**

**instantaneous power constraint**

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# Decentralized Optimization for Multichannel Random Access (DOMRA)

- Original problem: difficult to globally optimize
- Objective function is equivalent to:
  - reduce transmission collisions of the whole network.
  - maximize the achieved data rate of each BS with transmission capability limit.
- Problem decomposition:
  - Subproblem 1: find optimal thresholds
    - Resolves network collision
    - Achieve proportional fairness
  - Subproblem 2: find optimal power allocation policy
    - Optimize individual transmission performance
    - Satisfy average and instantaneous power constraints

# Optimal DOMRA - MAC Layer

- **Optimal predetermined threshold**

$$\overline{\mathrm{H}}^{*}_{(i,j)_k} = F^{-1}\left[ \left(1 - \frac{|T_i|}{|R_i| + \sum_{j \in N_i} |R_j|}\right)^{\frac{1}{|T_i|}} \right]$$

- **Neighborhood Information**

**Local knowledge:**

$|T_i|$ **: number of users receiving packets from User** ***i***

$|R_i|$**: number of users sending packets to User** ***i***

**Two-hop knowledge (typical in routing discovery):**

$\sum_{j \in N_i} |R_j|$**: total number of users sending packets to the interfering neighbors of User i**

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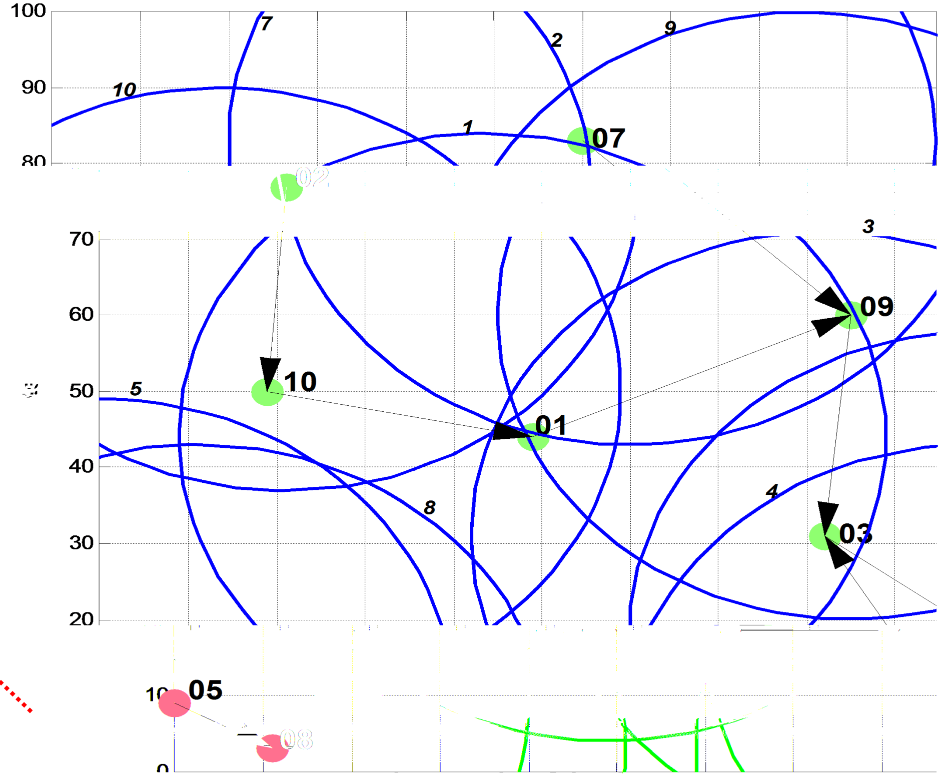
# Threshold Adaptation

$$\overline{H}^*_{(i,j)_k} = F^{-1}\left[(1 - \frac{|\mathcal{T}_i|}{|\mathcal{S}_i| + \sum_{m\in\mathcal{N}_i}|\mathcal{S}_m|})^{\frac{1}{|\mathcal{T}_i|}}\right].$$




Low threshold

Very high threshold

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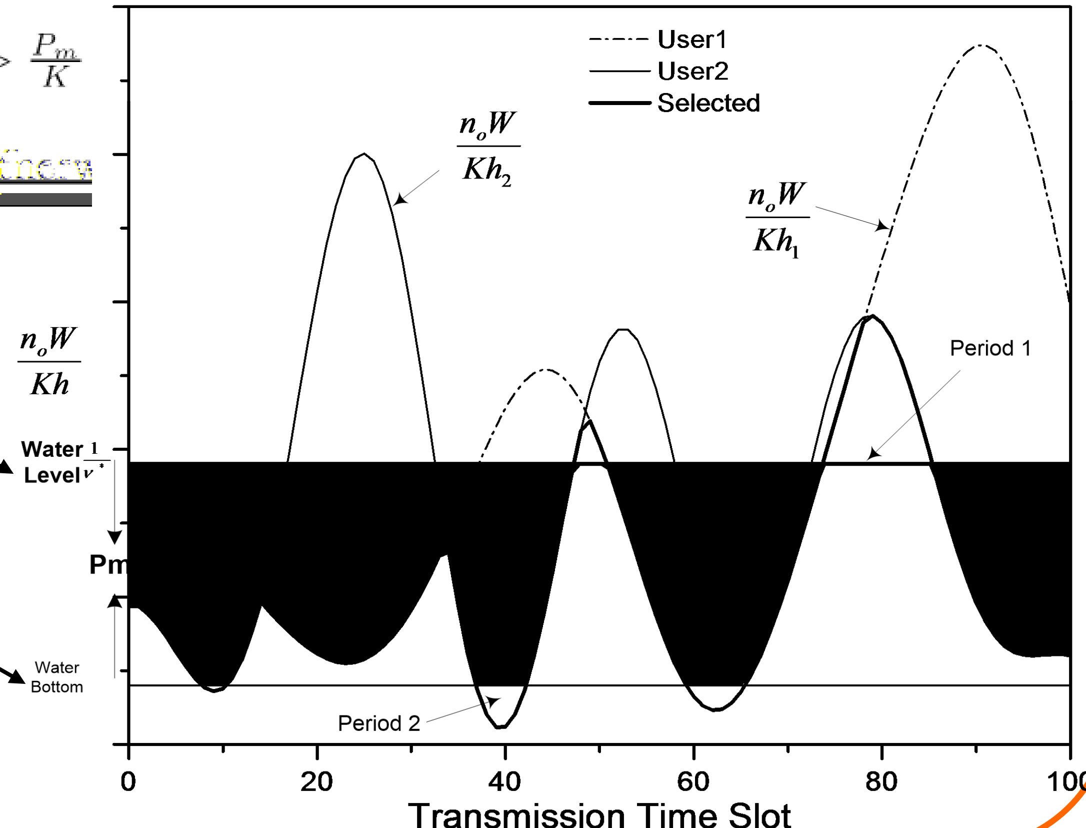
# Link Adaptation

- **Capability-limited water-filling power allocation**

$$P^*_{(i,j)_k}(h) = \begin{cases} \frac{P_m}{K} & \frac{1}{\nu^*} - \frac{n_o W}{Kh} > \frac{P_m}{K} \\ 0 & \frac{1}{h} \geq \frac{K}{\nu^* n_o W} \end{cases}$$

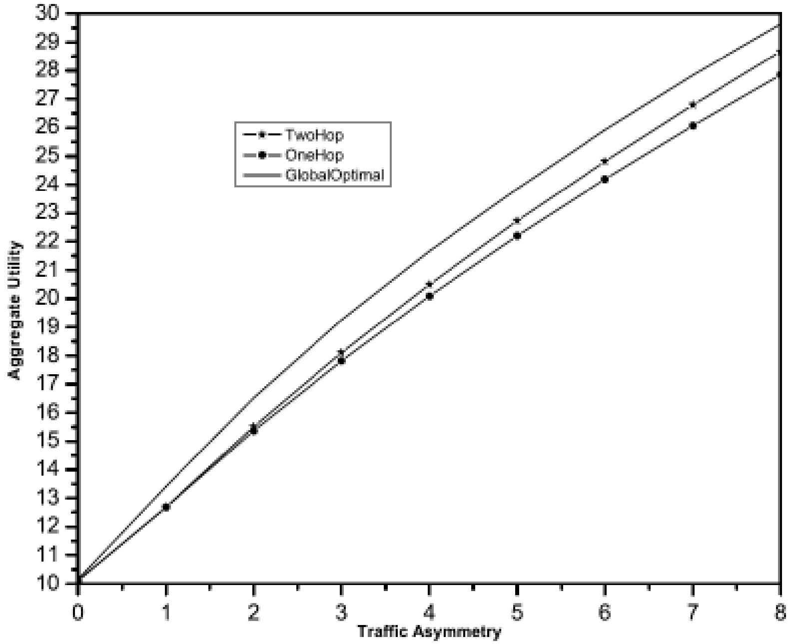
Due to average power constraint

Due to peak power constraint



# Sub-Optimality Gap

- Gap to the global optimum.
  - Obtain feasible decentralized policy through subproblem decomposition
  - Global optimum
    - Global network knowledge
    - Difficult to solve
    - Exhaustive search



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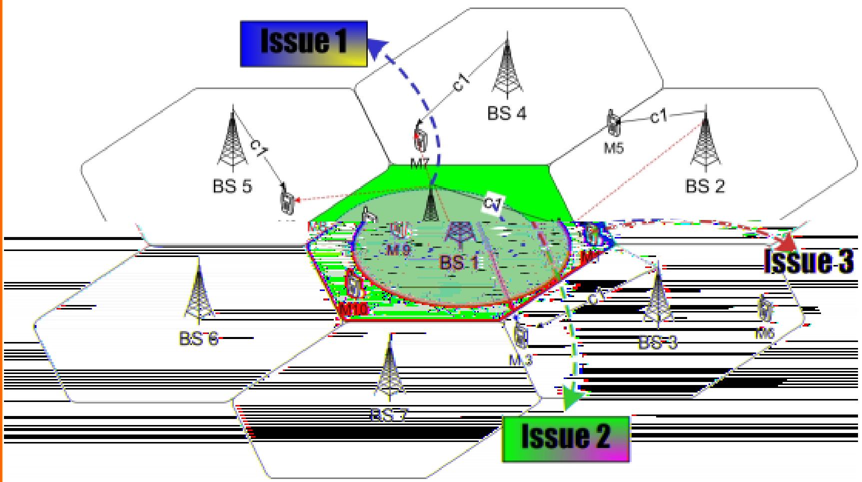
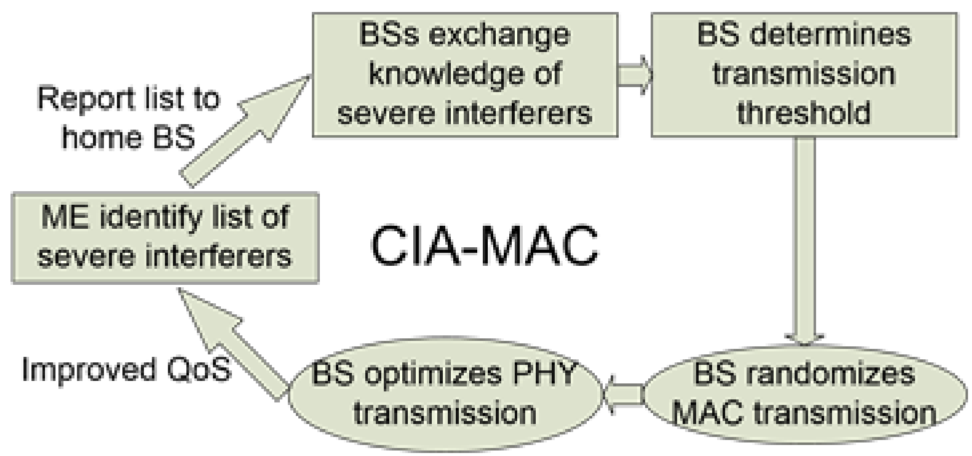
# Cochannel Interference Avoidance MAC (CIA-MAC)

- **Co-Channel Interference (CCI): the major factor limiting system capacity**
- **CIA-MAC: improve downlink QoS of cell-edge users**
- **Severe interferers: dominant interfering BSs; randomize transmission**




Optimized by: **DOMRA**

Threshold design to control BS random transmission

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# How to Decide Severe Interferer?

- **Severe Interference: no MAC frame recovered after CRC due to CCI**
  - **Interference to Carrier Ratio (ICR) of Interferer $i$:**

$$ICR_i = \frac{\mathrm{E}(|H_i|^2 P_i)}{\mathrm{E}(|H|^2 P)}$$

  - **Severe Interferer Judgment**
    - **Interferer $i$ is a severe interferer when**

$$ICR_i \geq \Gamma_c$$

    **where $\Gamma_c$ is named CIA-MAC trigger.**
  - **Transmission of severe interferer will always cause failure of packet reception in the MAC layer.**
- **CIA-MAC is triggered when it achieves better network throughput**

$$\Gamma_c = \frac{1}{P_e^{-1}\left[1-\left(\frac{K^K}{(1+K)^{K+1}}(1-P_e(\eta))^{L_d R \frac{R}{\bar{\bar{R}}}}\right)^{\frac{1}{L_d \bar{\bar{R}}}}\right]} - \frac{1}{\eta}.$$

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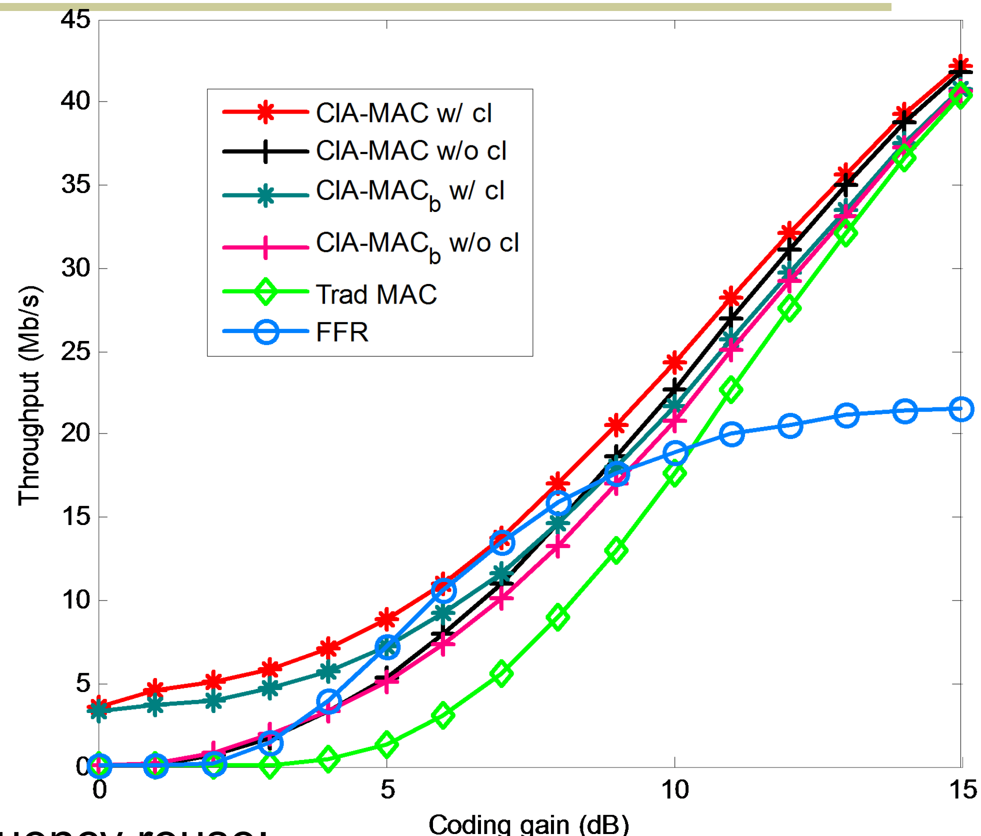
# Performance Improvement




CIA-MAC wins because: 1. full frequency reuse;

2. intelligent recognition of severe interferers.

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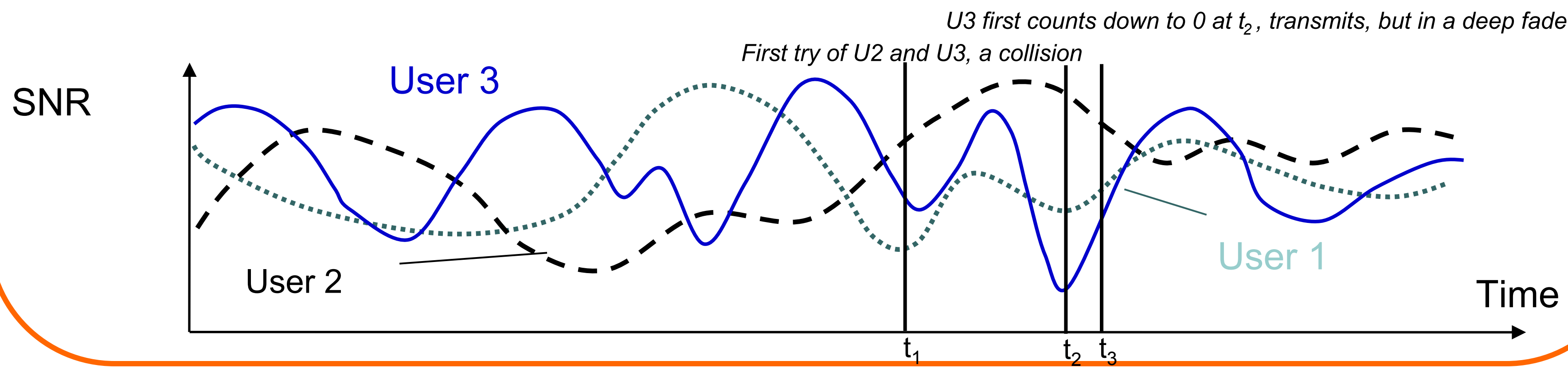
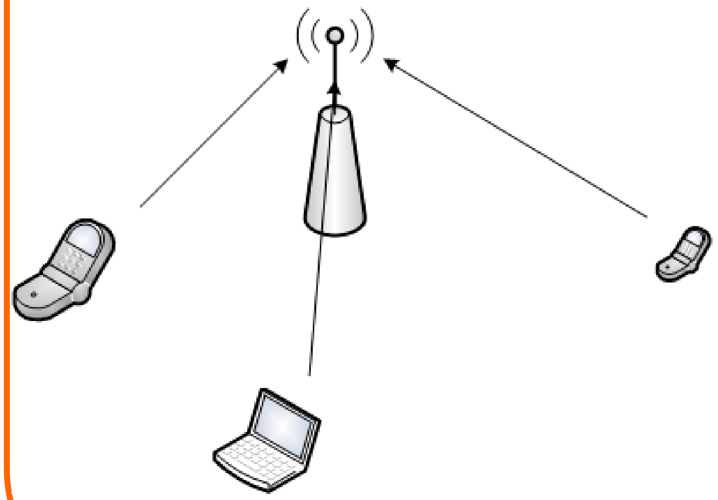
# Existing Random Access Schemes

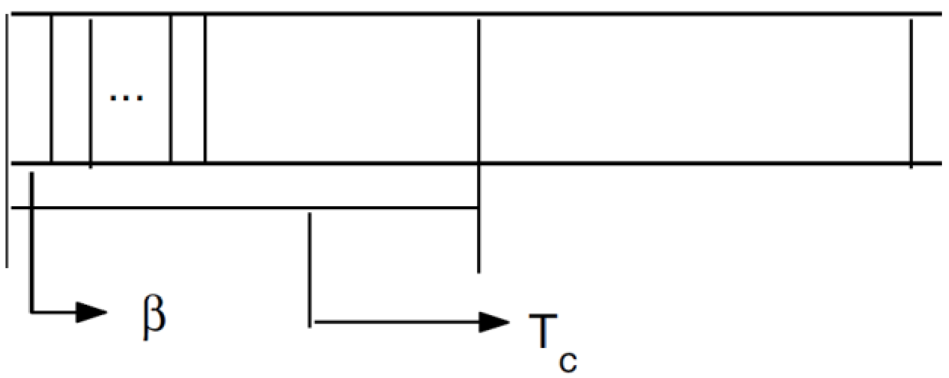
- Channel-Aware Aloha, DOMRA: Aloha based, collision of entire data frames result in low channel utilization
- Design signaling negotiation to avoid collision
- Existing schemes (e.g. CSMA-CA):
  - Backoff when collision without considering CSI
  - Drawback: deferring transmission may result in data communications in deep fades.



# Infrastructure Networks[Qin04]

- Opportunistic Splitting Algorithms
  - Distributed splitting algorithm to reduce this contention.
  - Resolve a collision and find the user with the best channel gain





# Opportunistic Splitting Algorithms [Qin04]

- In the beginning of each mini-slot, users with $H_l$<h< $H_h$ will transmit
- At the end of each mini-slot, BS feeds back (0, 1, e) to all users
  - 0: idle
  - 1: success
  - e: collision
- Users update the two thresholds, $H_l$ and $H_h$ , and continue contention in the following mini-slots.
  - Updates to minimize the collision probability in the following mini-slots
  - Example: e: increase $H_l$ to reduce the number of users in the range
- Finally only one user is expected to have gain $H_l$<h< $H_h$ .

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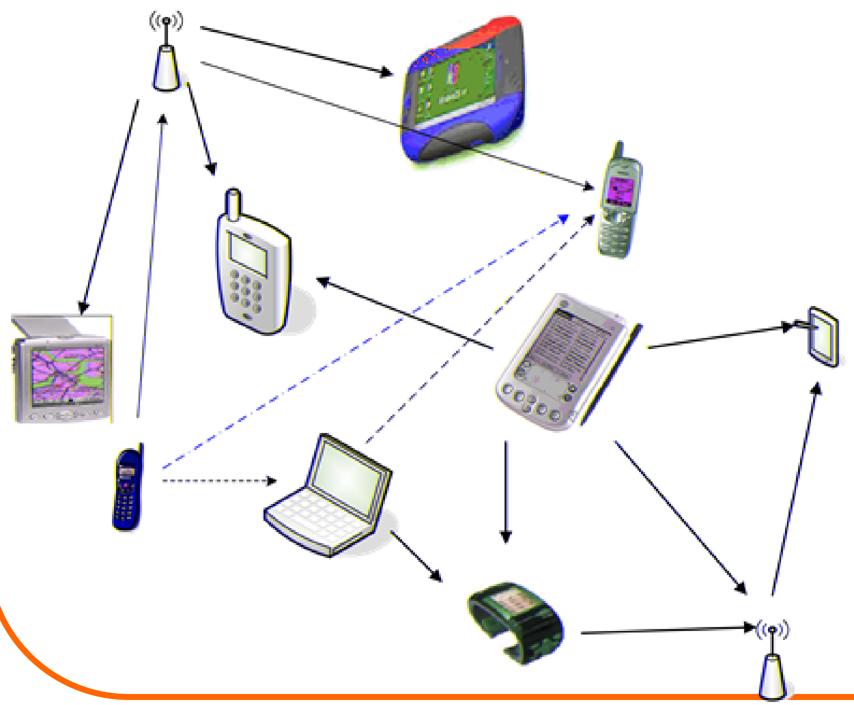
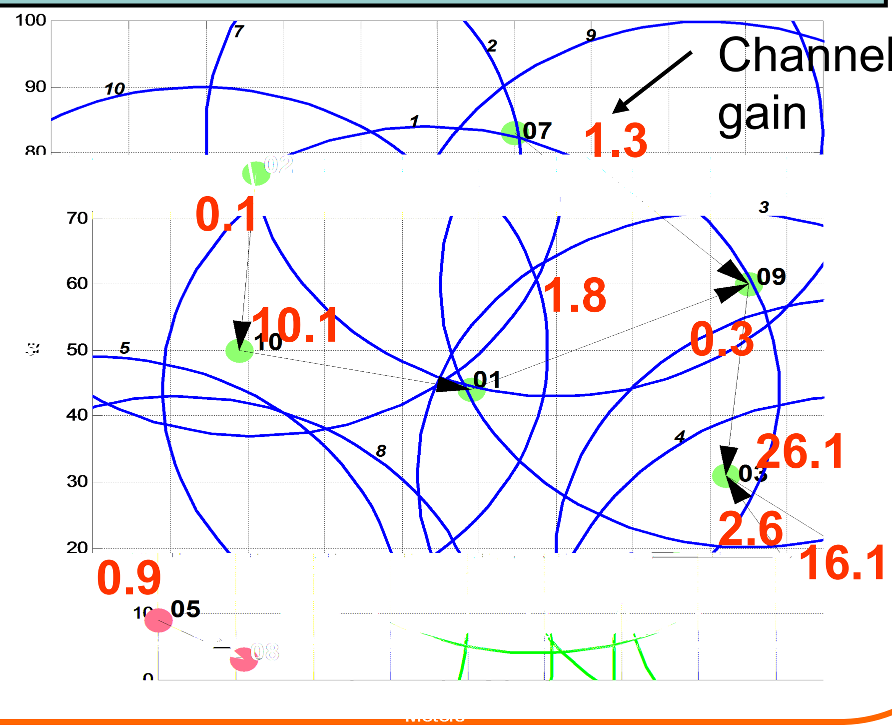
# Ad Hoc Networks

**Can distributed random access algorithms achieve the performance of centralized algorithms? How to do it?**





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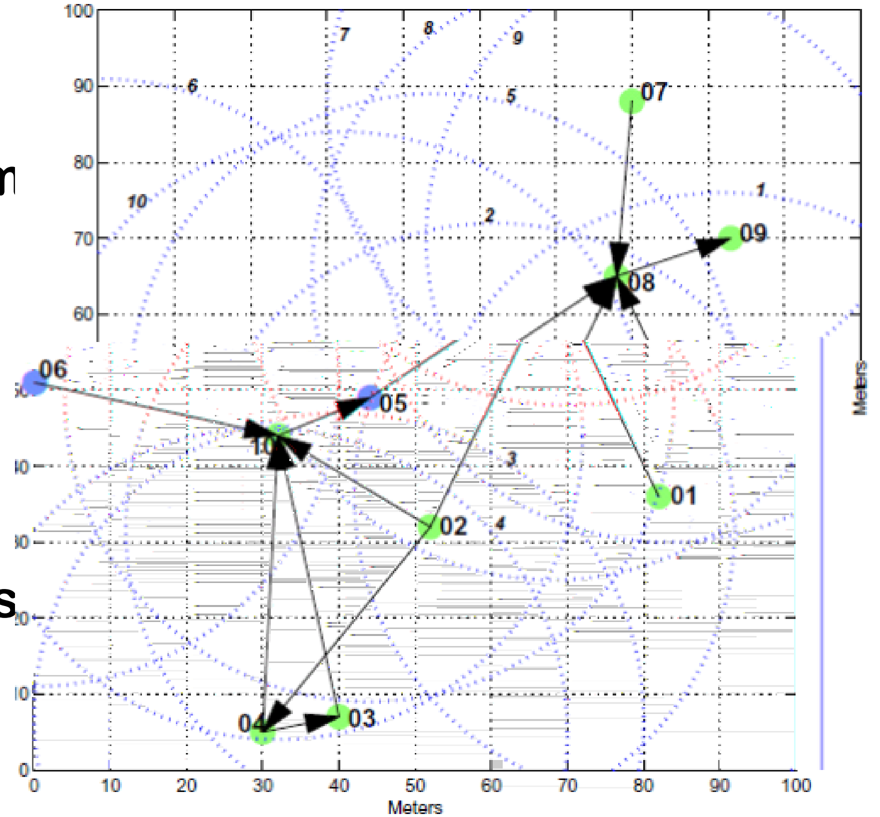
# Channel Aware Distributed MAC (CAD-MAC)

- Different traffic flows contend for channel access
  - Senders determine channel access
  - Two types of contentions
- Type-I contention
  - Links with the same transm
  - Central scheduling
    - (2,4), (2,8), and (2,10)
- Type-II contention (focus)
  - Among all other links
  - Distributed random access
    - (2,4) and (3,10)



# Resolution of Type-I Contention

- **Different channels experience gains of different distributions**
- **Self-max-SNR scheduler**

channel gain

$$j = \arg\max_{l} F_{il}(h_{il})$$

Distribution of corresponding channel gain

E.g.: Rayleigh fading

$$j = \arg\max_{l} \frac{h_{il}}{\overline{h_{il}}}$$

1. All links are scheduled with equal probability (fairness assurance)
2. Always schedule the link with the best instantaneous channel condition relative to its own channel condition (performance assurance)
3. Same as max-SNR scheduler when all links are with i.i.d. channel distribution

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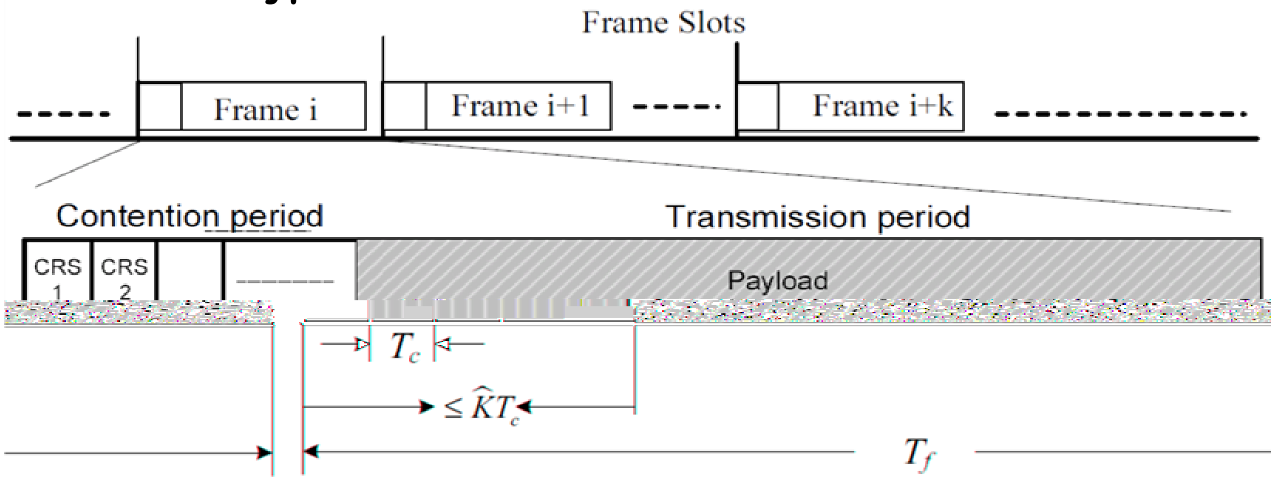
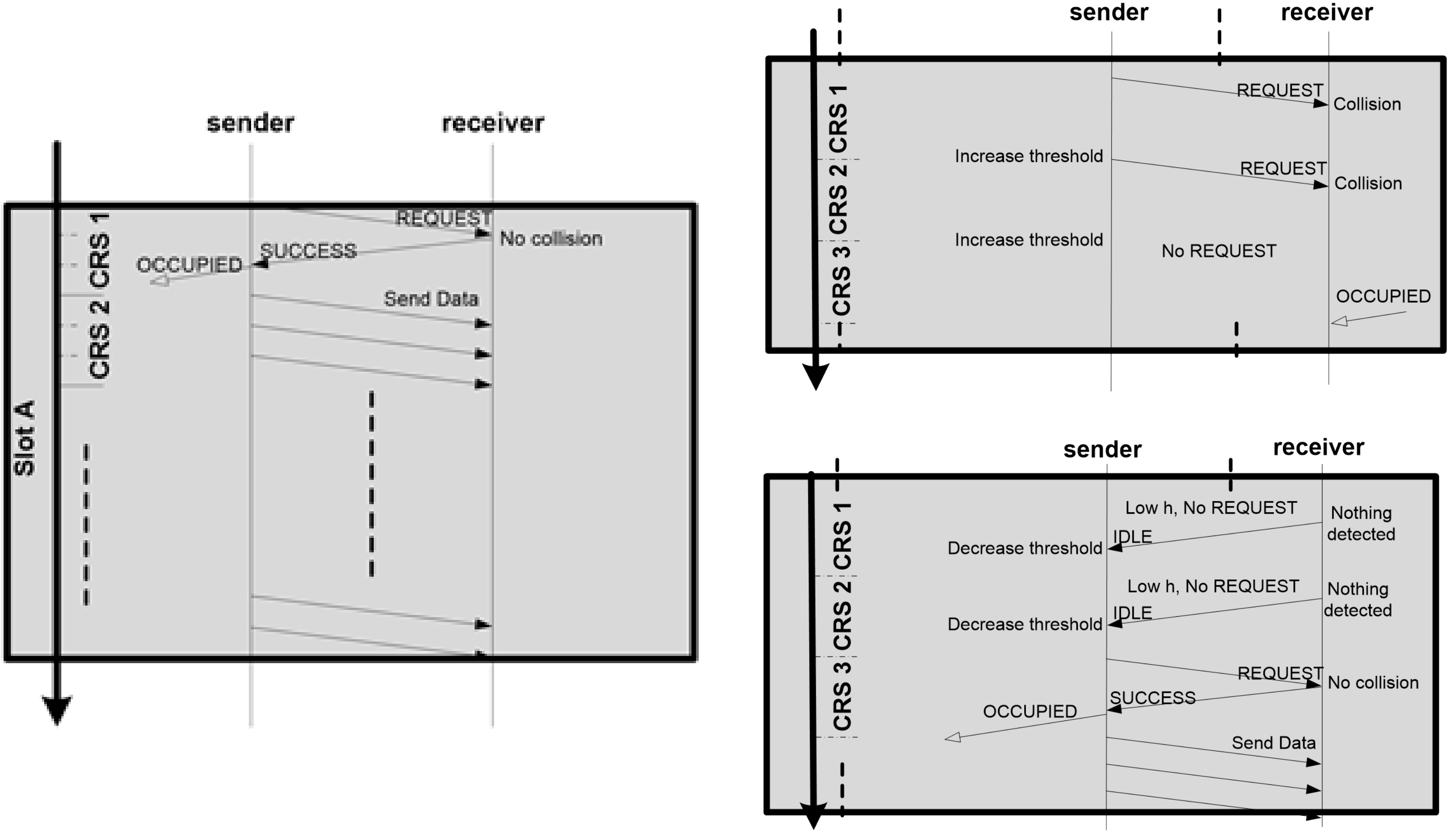
# Resolution of Type-II Contention

**Users selected in Type-I contention resolution are involved.**




- **1. Resolve contention in each CRS through a multi-stage channel-aware Aloha (similar to DOMRA, use threshold to control contention performance and fairness)**
- **2. After one CRS, links with higher gains selected in a distributed way to continue the contention in the following CRS (through distributed threshold control )**
- **3. Only one link with the best channel gain wins within each local area for data transmission, all neighbors informed to keep silent**

# Three-Step Signal Exchange



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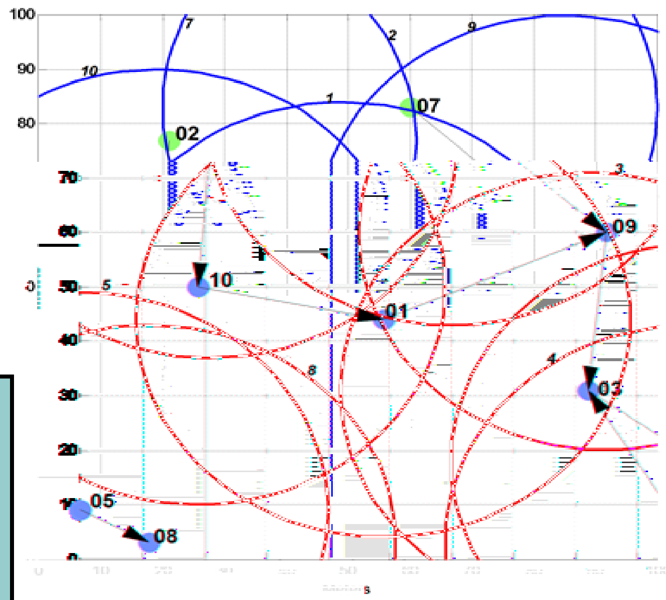
# Complete Contention Resolution

Definition: The contention in a network is Completely resolved if

1. all links that have won the contention can transmit without collision;
2. if any additional link that has not won the contention transmits, it will collide with at least one link that has won the contention.




**Theorem 1:** ***With probability one, the contention of any networks can be completely resolved by CAD-MAC if sufficient CRSs are allowed.***

**CAD-MAC comparable to centralized schedulers**

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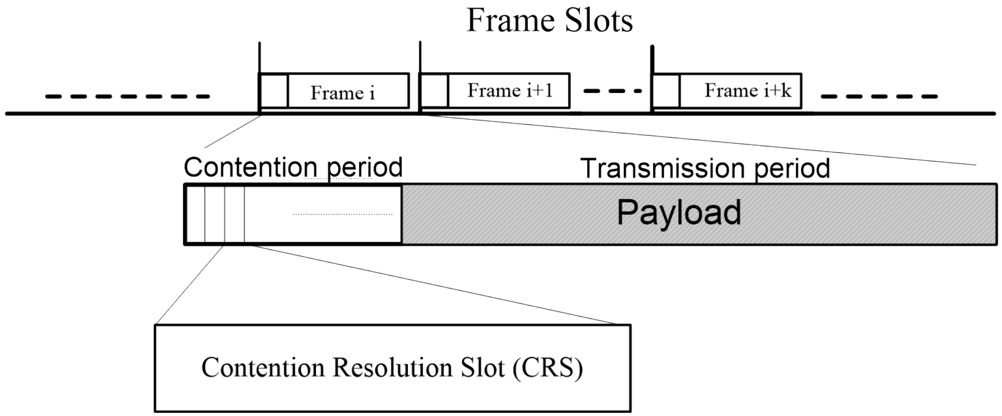
# Efficiency

- **Performance loss compared to a centralized scheduler**
  - **Due to CRSs used to resolve the contention**




  - **Define the efficiency of CAD-MAC to be:**

$$\gamma = \frac{T_{CAD-MAC}}{T_{Centralized}} = 1 - \frac{\overline{K}T_c}{T_f}$$

$\overline{K}$ **: average number of CRSs resolving contention**

$T_c$ **: CRS length;** $T_f$**: frame length**

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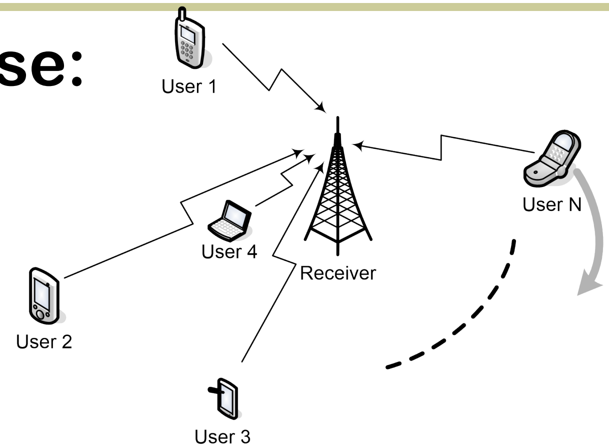
# Necessary CRSs

- **A special case:**




Theorem 2: *For a network with N links, each interfering with all others,*

$$\overline{K}_N \leq \frac{\widehat{M}_N}{1-(1-\frac{1}{N})^N} + \frac{(1-\frac{1}{N})^N}{(1-(1-\frac{1}{N})^N)^2}$$

*where* $\widehat{M}_N = \sum_{n=1}^{N} \binom{N}{n} (\frac{1}{N})^n (1-\frac{1}{N})^{N-n} (\log_2(n)+1)$

*Furthermore,*

$$\overline{K}_N < \overline{K}_\infty \leq 2.43$$

# Necessary CRSs

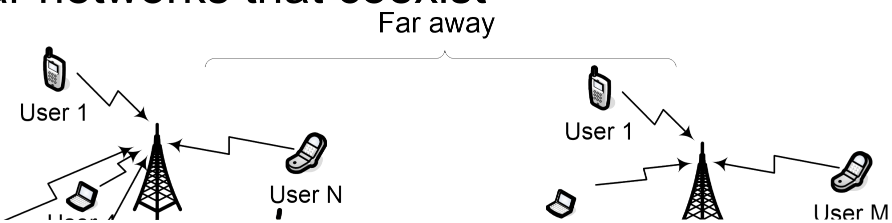
Theorem 3: *For a network of* ***any type and size****,*

$$\overline{K} < \frac{2.43 \cdot \overline{L}}{\beta}.$$

$\overline{L}$: transmission coexistence factor, *the average number of links that win the contention in one frame slot*

$\beta$: *contention coexistence factor, the average number of simultaneous resolutions in each CRS*

Examples: two cellular networks that coexist



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# Efficiency of CAD-MAC

Proposition 1: *The efficiency of CAD-MAC satisfies,*

$$\gamma > 1 - \frac{2.43 \cdot LT_c}{\beta T_f}.$$

*For a network where each user interferer with all others,*

$$\gamma > 1 - \frac{2.43 \cdot T_c}{T_f}.$$

**CRS length $T_c$: round-trip time of signal propagation**

**Frame length $T_f$: channel coherence time**

**Example:**

- **Cellular networks of 6km radius**

  **round trip time: 50 $\mu s$ [Leung 2002]**

  **channel coherence time: tens of milliseconds with 900 MHz carrier frequency and user speed 72 km/h [Kumar 2008]**

**Efficiency close to unity.**

# Robustness of CAD-MAC

- **What if users have imperfect CSI because of non-ideal channel estimation?**
  - **Control medium access based on** $\{\widetilde{h}_{ij}\}$ **and** $\{\widetilde{F}_{ij}()\}$

**rather than the actual** $\{h_{ij}\}$ **and** $\{F_{ij}()\}$

Theorem 3: *Theorems 1, 2, and 3 and Proposition 1 hold when all users have imperfect channel knowledge and CAD-MAC is robust to any channel uncertainty.*

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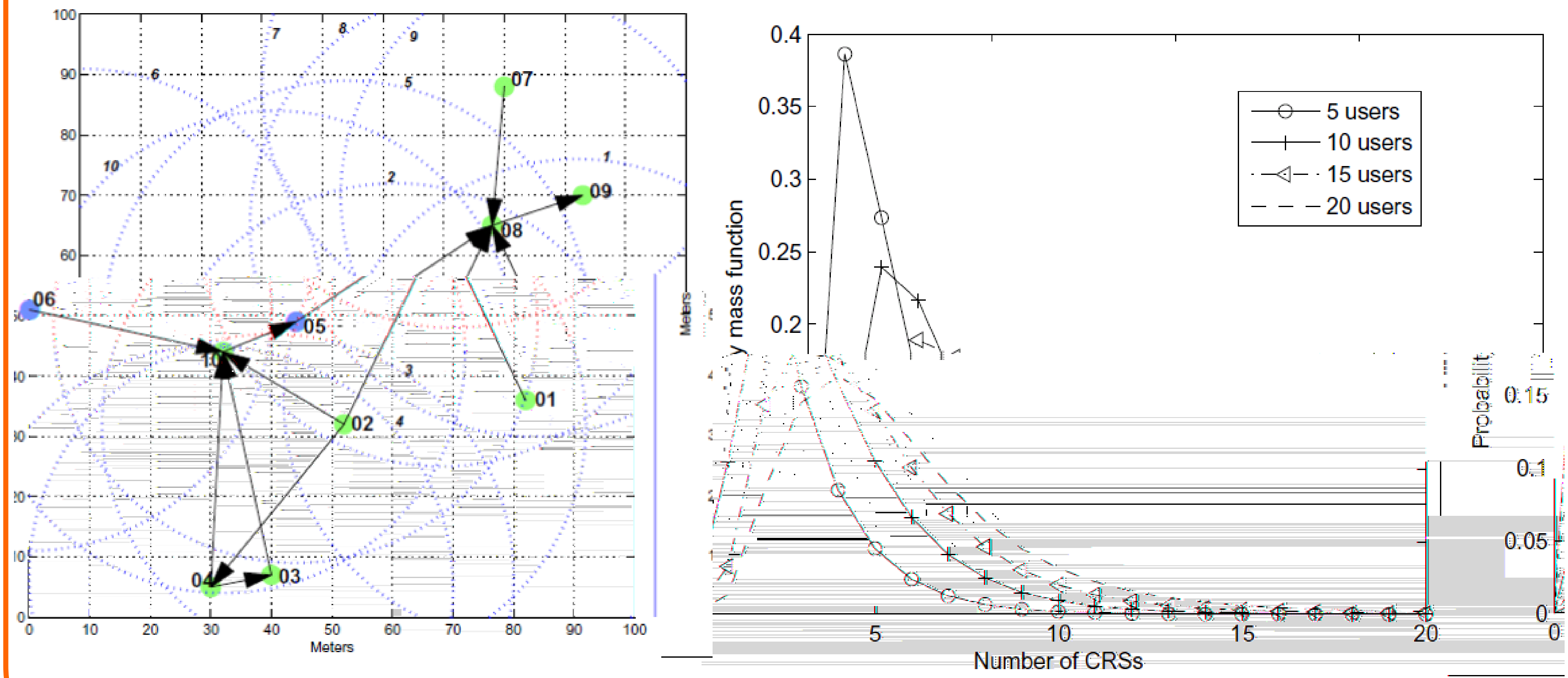
# Simulation Performance – CRSs Needed for Complete Contention Resolution



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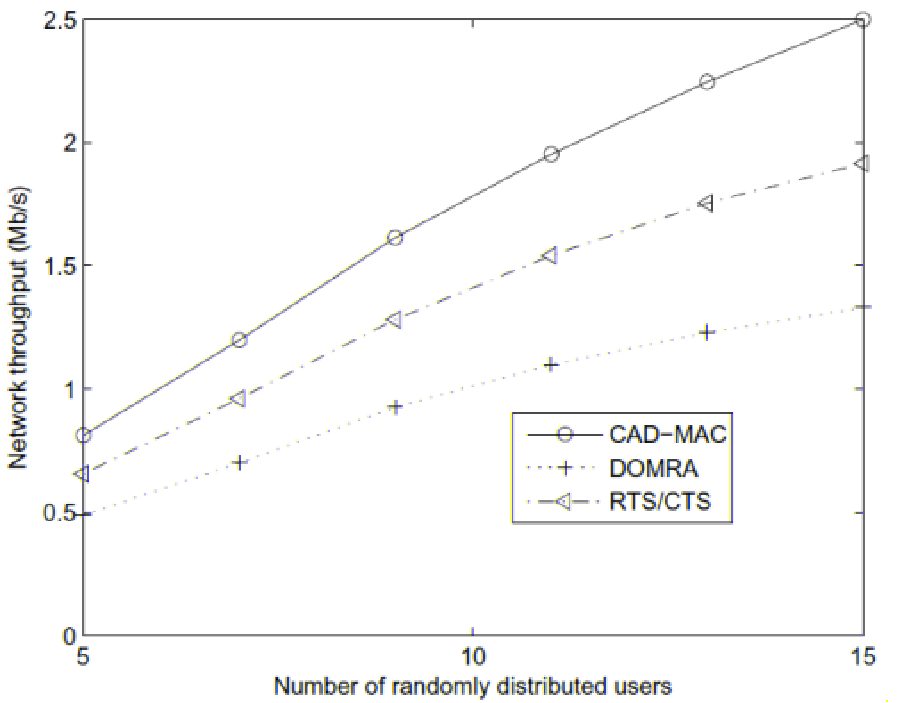
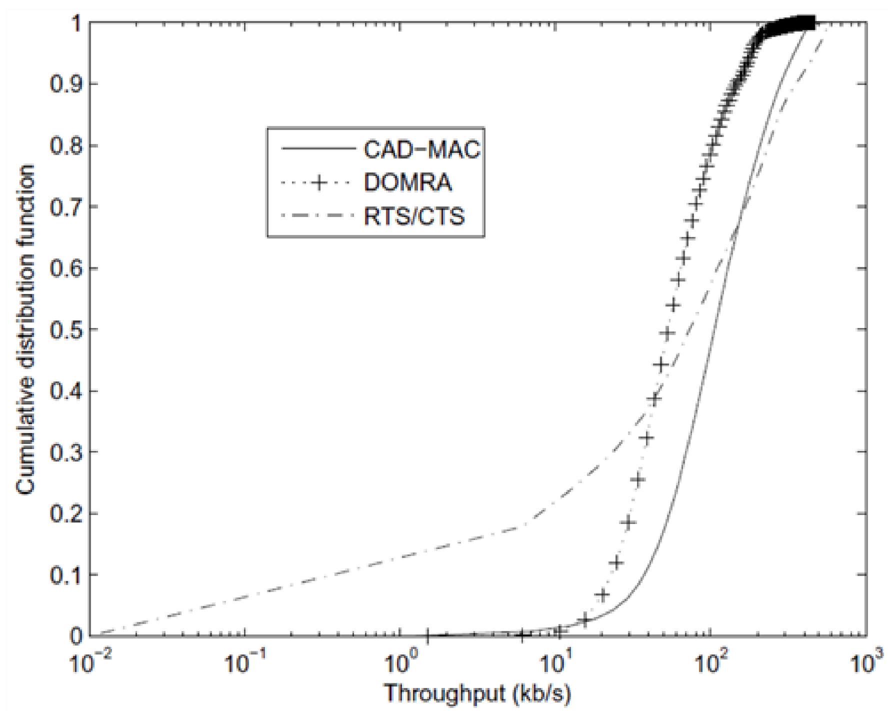
# Simulation Performance



# 5. CROSS-LAYER OPTIMIZATION FOR ENERGY EFFICIENCY

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# Energy Saving $\neq$ Energy Efficiency

- **Complete Saving of Energy**
  - **Shut down network completely to save the most energy**
  - **Not desired!**

- **Purpose of energy-efficient wireless network design**
  - **Not to save energy**
  - **Make the best/efficient use of energy!**

**Energy saving**
**w/o**
**losing service quality**

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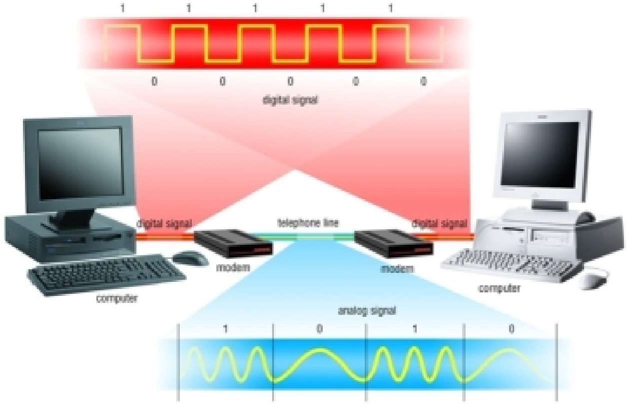
# Energy and Communications

- What is energy?

**The ability to move things**

- Essence of communications
  - Use energy to move information from sender to receiver



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# Transmit Power Concern

- **Information theorists studied energy-efficient communications for at least two decades [Gallager88,Verdu90]**
  - **Transceivers designed to maximize information bits per unit energy**
  - **Use infinite degrees of freedom per bit, e.g. infinite bandwidth or time duration**
    - **Example:**
      - **Energy consumption per bit in AWGN channels:**

$$E = \hat{P}t = \left(2^{\frac{1}{Wt}} - 1\right) W N_0 t / g,$$

      - **Minimized when t or W is infinite**

$$E_{min} = No \ \ln 2 / g$$

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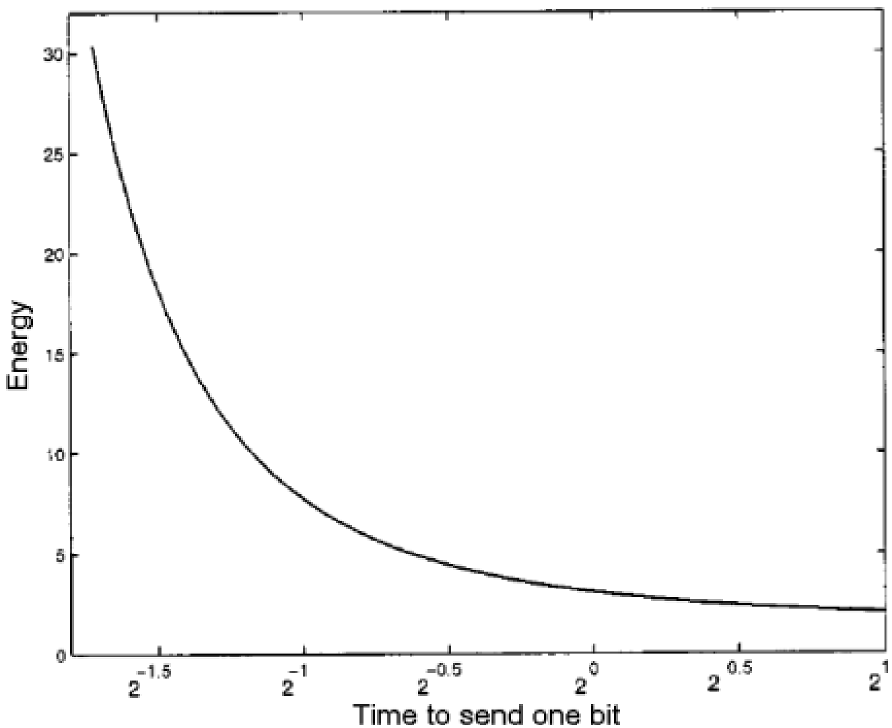
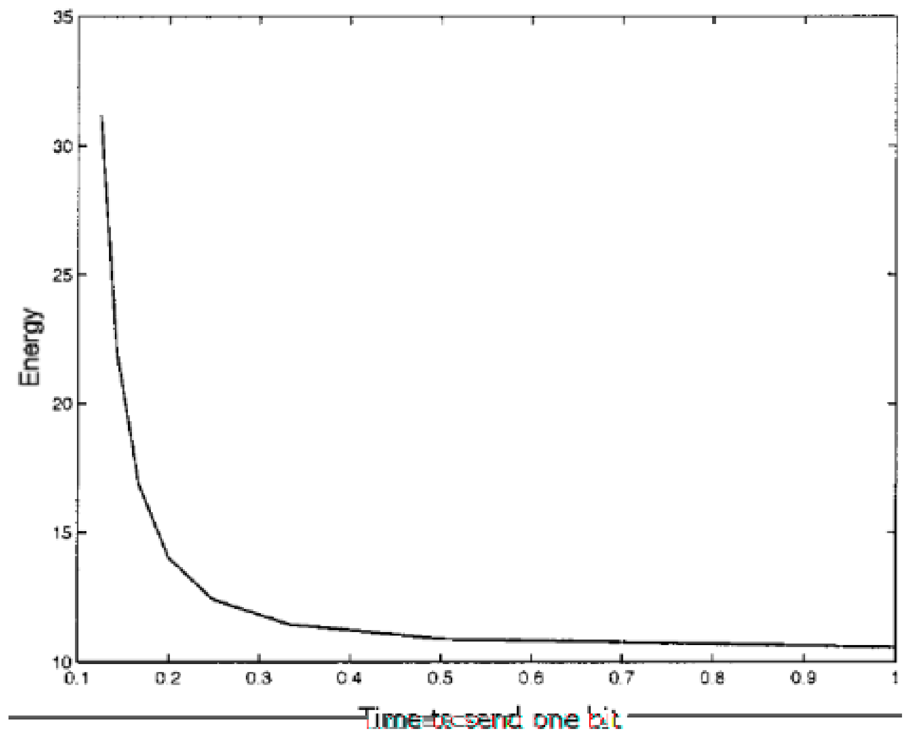
# Energy Consumption Per Bit




Optimal Coding




Uncoded MQAM

[Prabhakar01]

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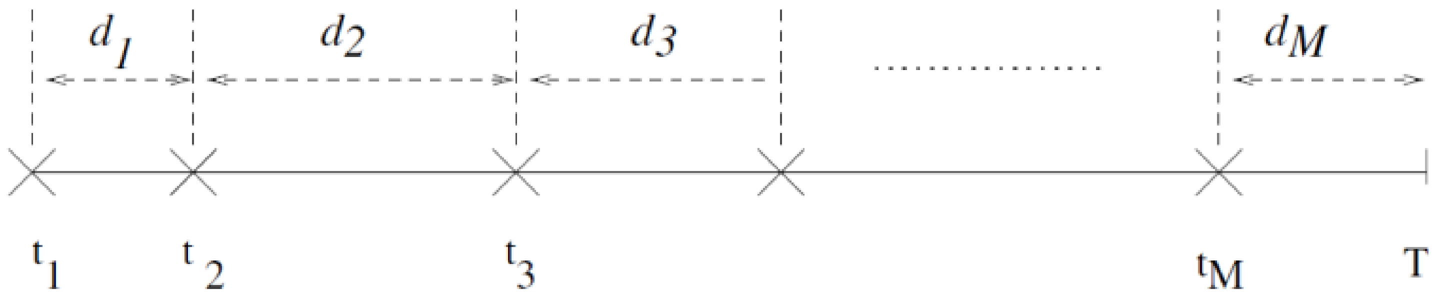
# Lazy Packet Scheduling [Prabhakar01]

- **Minimize energy to transmit packets within a given amount of time.**




**Packet arrival time $t_i$.**
**All packets are of the same size.**

**Question: what's the transmission duration for each packet so that the total energy transmitting all the packets is minimized?**

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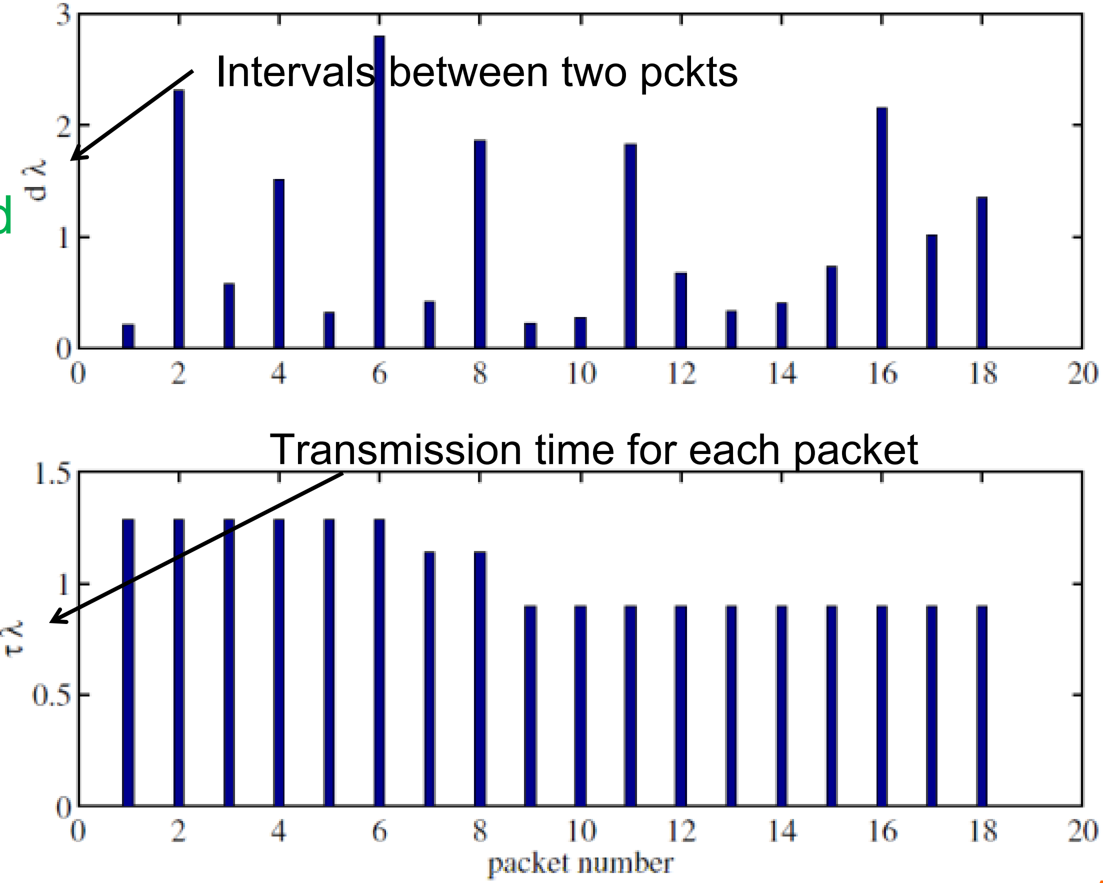
# Optimal Offline Scheduling

Answer: divide available transmission time evenly among all packets and extend the transmission time as long as possible




Optimal online scheduling: exploit this property while considering

1. current buffer size
2. future arrivals (statistics of arrival process)
3. time left

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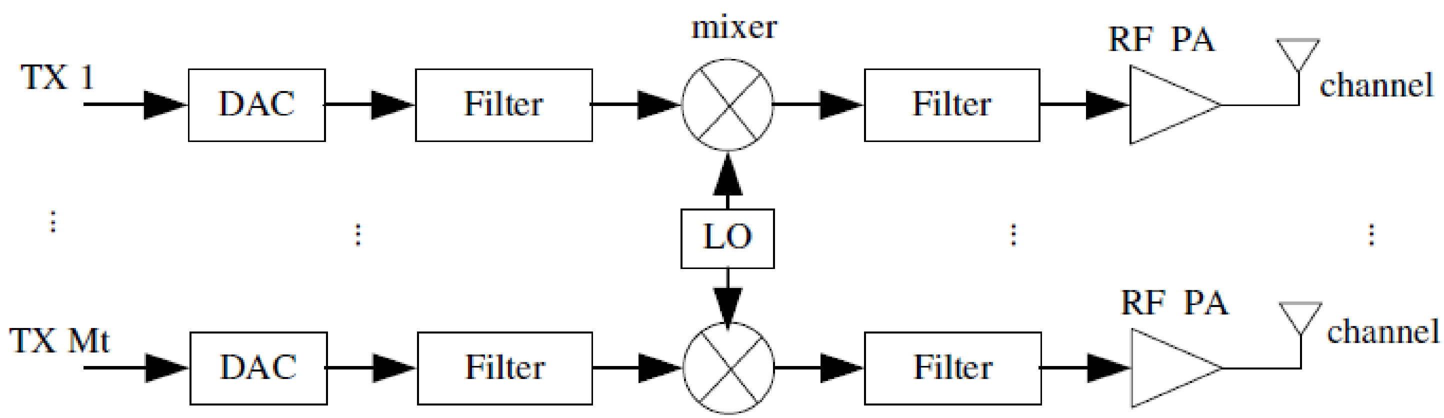
# Energy Consumption in Practice




- **RF transmit power:**
  - **Consumed by PA for reliable delivery of data**
- **Circuit component power:**
  - **Consumed by electronic circuits for reliable device operations**

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# A Detailed Analysis of Energy Consumption

| Components | Power Model Parameters | Transmit Mode | Idle/Receive Mode |
|---|---|---|---|
| PA | $PAR$, $d$, $b$, $SER$, $R_s$ | 126.5 mW | 0 mW |
| Mixer | $K$,$NF$ | 21 mW | 21 mW |
| Freq. Syn. | $\omega_c$, $F_{LO}$, $F_{ref}$ | 67.5 mW | 67.5 mW |
| LNA | $A$, $NF$ | 0 mW | 20 mW |
| ADC | $PAR$, $SQNR$, $f$ | 0 mW | 5.85 mW |
| DAC | $PAR$, $SQNR$, $OSR$ | 15.4 mW | 0 mW |
| Filter | $f$, $SNR$ | 2.5 mW | 2.5 mW |
| Baseband Amplifier | $B$, $\alpha_{BA}$ | 0 mW | 5 mW |
| Ref. System | $V_{dd}$, $I_{ref}$ | 0.5 mW | 0.5 mW |
| Total | $N/A$ | 233.4 mW | 122.35 mW |

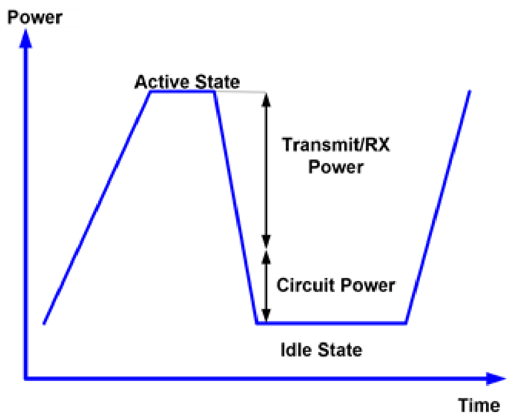
[Li, Bakkaloglu, and Chakrabarti, 07]

miao@FreeLinguist.com

# Our Interest: Wireless Solution

**Power consumption of 802.11 transceivers[Man05]**

| Mode | 802.11b | 802.11a | 802.11g |
|---|---|---|---|
| Sleep | 132 mW | 132 mW | 132 mW |
| Idle | 544 mW | 990 mW | 990 mW |
| Receive | 726 mW | 1320 mW | 1320 mW |
| Transmit | 1089 mW | 1815 mW | 1980 mW |




**Transmit mode** critical for power consumption

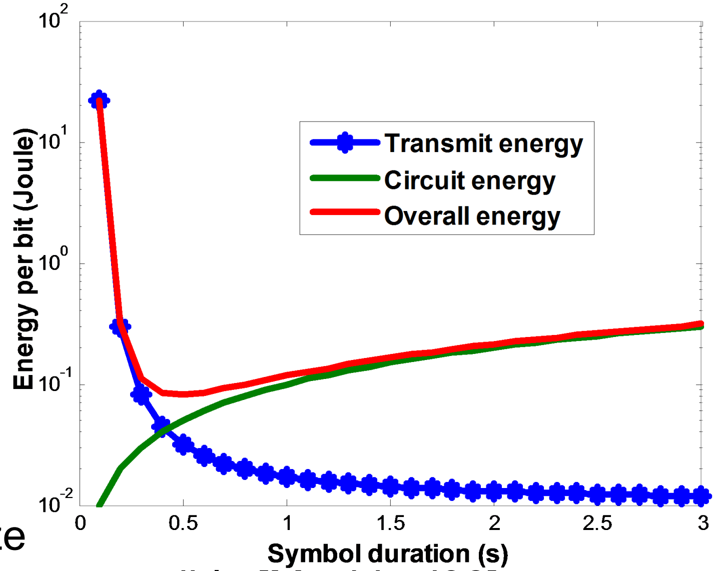
- Radio interfaces account for more than 50% of overall system energy budget for a smart cellular phone [Anand2007].
- Selection is critical

Our focus: **transmit mode**

Emphasize PHY and MAC to improve energy efficiency in transmit states

# Another Look at the Issues

- **Circuit power** *Pc*
  - Used by all other electronics (filters, AD/DA)
  - Device dependent
  - A fixed energy cost in transmit mode
- **Transmit power** $P_T(\boldsymbol{R})$
  - Used by power amplifier for reliable bit transmission
  - Power for reliable transmission of ***R***
  - Depend on modulation, coding and channel
  - Selection of ***R*** determines energy efficiency




Need to balance <u>conflicting design guidelines</u> to optimize

Transmit energy: Extend transmission time as long as possible [Meshkati06], [Prabhakar01]

Circuit energy: Use highest rate supported and finish transmission ASAP

**How to optimize the balance between transmit & circuit energy?**
**Across all subchannels?**

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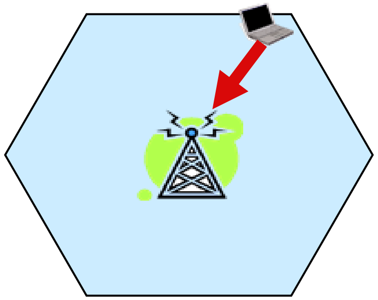
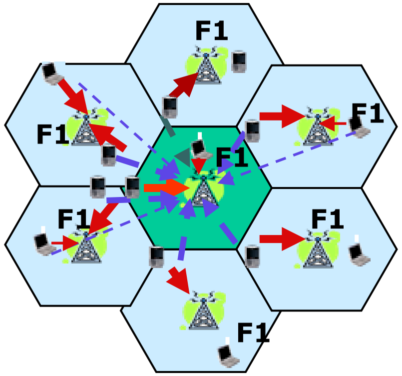
# Energy-Efficient OFDM and MIMO

**OFDM and MIMO:**

- Key technologies in next-generation wireless communications
- Few work done for energy-efficient OFDM and MIMO




- Approach
  - Allocate power, adapt modulation and coding based on channel state information to
    - reduce power consumption of point to point links;
    - and balance the competing behaviors of multicell energy-efficient communications

# Energy Efficiency Metric

- **Send as much data as possible given a certain amount of energy**
- **Given any small amount of energy** $\Delta C$ **consumed in a transmission duration of** $\Delta t$ **, send a maximum amount of transmitted data** $R\Delta t$
- **Choose the optimal link adaptation, i.e. power and MCS (modulation and coding scheme), to maximize**

  $$\frac{R\Delta t}{\Delta C}$$

  **which is equivalent to maximize**

  Overall data rate on all subchannels

  $$U(R) = \frac{R}{\Delta C / \Delta t} = \frac{R}{P_C + P_T(\mathbf{R})}$$

  Vector, data rates on all subchannels

  **called energy efficiency with a unit bits per Joule.**
- **Different from existing throughput maximization schemes: variation of overall transmit power**

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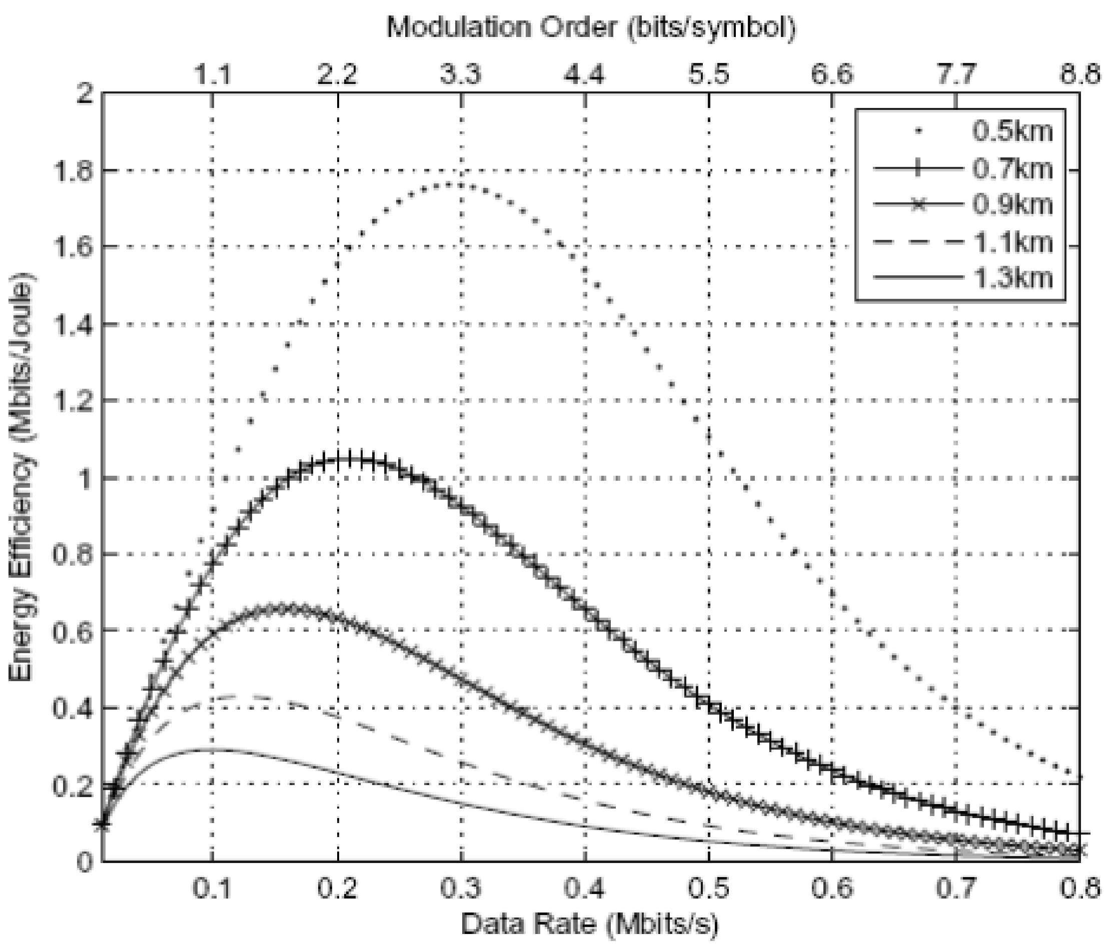
# Energy Efficiency in Flat Fading Channel



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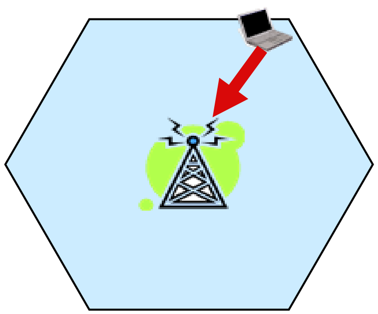
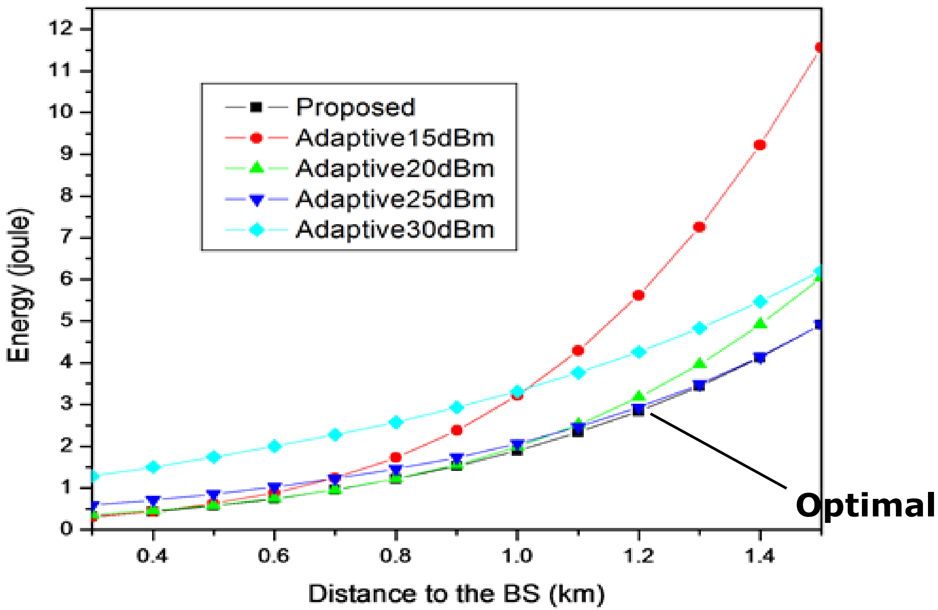
# Optimal Energy Efficient Link Adaptation in Flat Fading Channels

- *Optimal energy efficient transmission rule [Miao07]*

$$R^* = \frac{P_c + P_T(R^*)}{P_T'(R^*)}$$






**Energy Consumption to transmit 1 Mb of data**

**Mobile users always operate with optimal modulation mode with optimal energy-efficient link adaptation**

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## Properties of Energy-Efficient Link Adaptation

- To improve energy efficiency, we should
  - Increase channel gain
  - Reduce circuit power
  - Increase the number of subchannels

- The data rate, determined by link adaptation, should
  - Increase with channel gain
  - Increase with circuit power
  - Decrease with the number of subchannels

[Miao, TCom10]: Relationship of energy efficiency, distance, and rate

# Upper Bound

- **Upper bound** of energy efficiency $\frac{1}{P_T'(0)}$

**With Shannon capacity, it is** $g/(N_o \ln 2)$ .

- **How to achieve it?**
  - **1. Zero circuit power and transmit with infinite small data rate**
  - **2. Infinite number of subchannels and transmit with infinite small data rate.**

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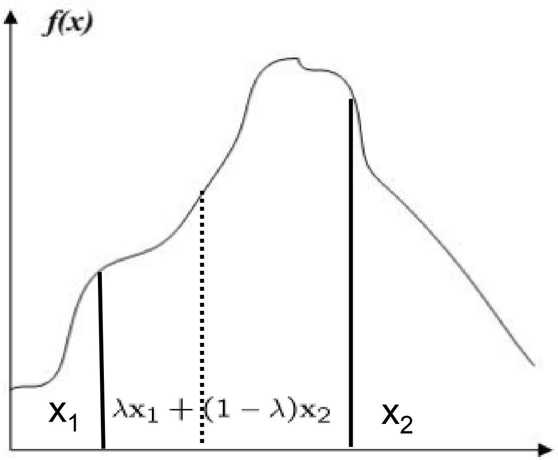
# Conditions for Global Optimum

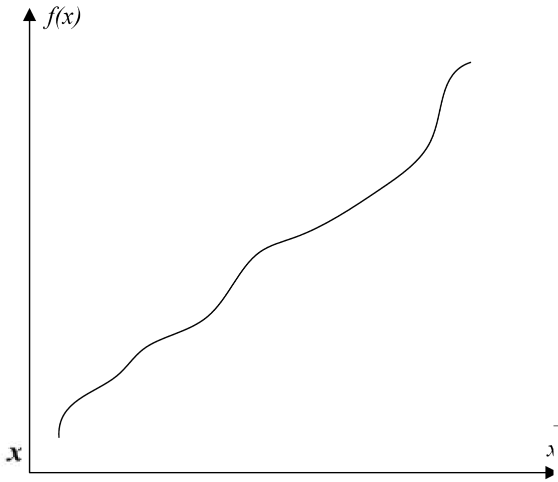
- **Concept of Quasiconcavity:**

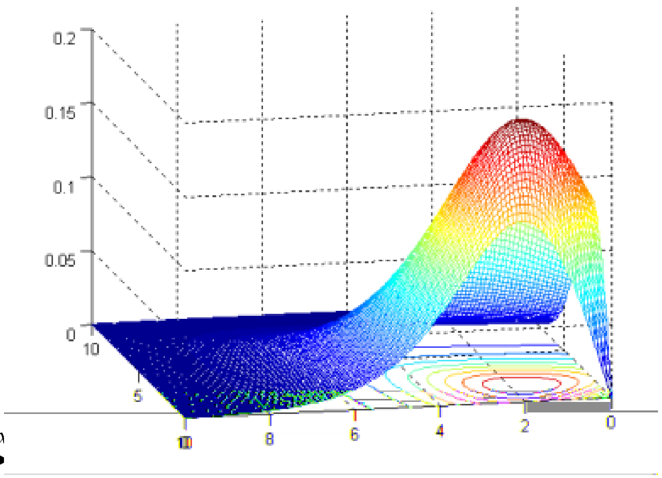
$$f(\lambda \mathbf{x}_1 + (1-\lambda)\mathbf{x}_2) > \min\{f(\mathbf{x}_1), f(\mathbf{x}_2)\},$$

for any $0 < \lambda < 1$.

- **A local maximum is also a global maximum**



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# Optimal Energy-Efficient Transmission

- **Energy efficiency** $U(\mathbf{R}) = \frac{R}{P_C + P_T(\mathbf{R})}$
  - **strictly quasiconcave**
- **A unique global optimal link adaptation exists and is characterized by**

Measure how good a subchanel is

1. If $\frac{P_C+P_T(\mathbf{R}_i^{(0)})}{R_i^{(0)}} \geq \left.\frac{\partial P_T(\mathbf{R})}{\partial r_i}\right|_{\mathbf{R}=\mathbf{R}_i^{(0)}}$,

$$\frac{\partial P_T(\mathbf{R}^*)}{\partial r_i^*} = \frac{P_C+P_T(\mathbf{R}^*)}{R^*} = \frac{1}{U(\mathbf{R}^*)}$$

2. If $\frac{P_C+P_T(\mathbf{R}_i^{(0)})}{R_i^{(0)}} < \left.\frac{\partial P_T(\mathbf{R})}{\partial r_i}\right|_{\mathbf{R}=\mathbf{R}_i^{(0)}}$, $r_i^* = 0$,

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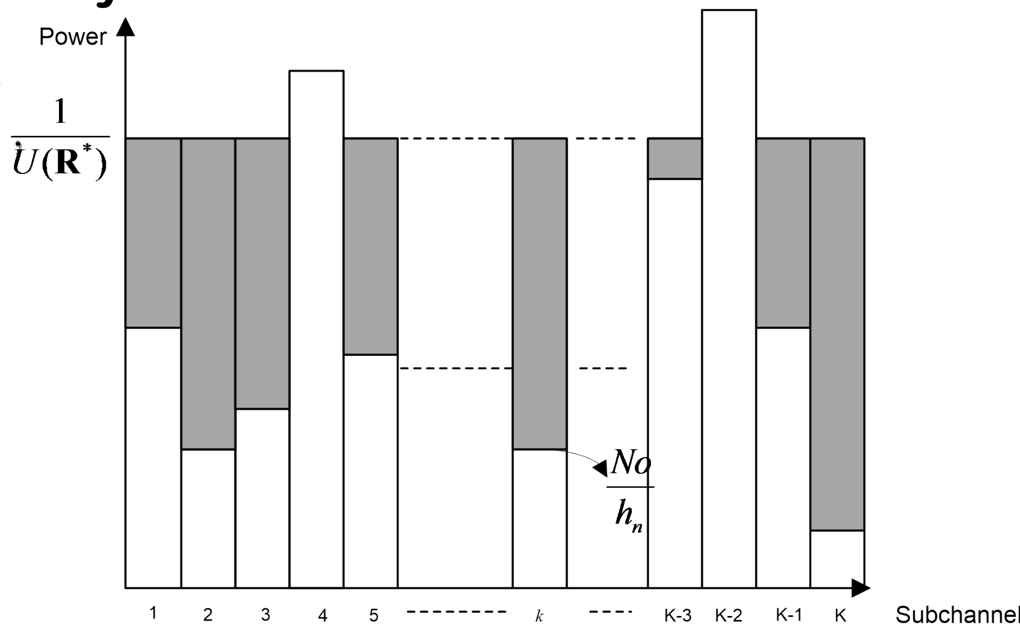
# Optimal Energy-Efficient Transmission

- **Example: Shannon capacity achieved on each subchannel:**

$$P_n = \left[\frac{1}{U(\mathbf{R}^*)} - \frac{N_o}{h_n}\right]^+$$




**dynamic water-filling**

- **Classical water-filling**

$$P_n = \left[\lambda - \frac{N_o}{h_n}\right]^+,$$

**where $\lambda$ is determined by the peak power limit**

**Optimally balance circuit energy consumption and transmit energy consumption on all OFDM subchannels**

# Energy-Efficient Downlink Transmission

- A generic EE transmission theory
  - Find $P_T(R)$
- Example: BS downlink OFDMA transmission [Xiong11]
  - A special case of wireless transmission
  - Except: before transmission, the BS needs to assign the subcarriers to users according to certain rules.
  - After scheduling: the base station needs to determine transmission modes

$$P_T(\mathbf{R}) = \sum_{k,n} \rho_{k,n}(\zeta p_{k,n} + \xi r_{k,n}) = \zeta \sum_{k,n} \rho_{k,n}(e^{\frac{r_{k,n}}{W}} - 1)\frac{N_o W \Gamma}{g_{k,n}\zeta} + \xi \sum_{k,n} \rho_{k,n} r_{k,n}.$$

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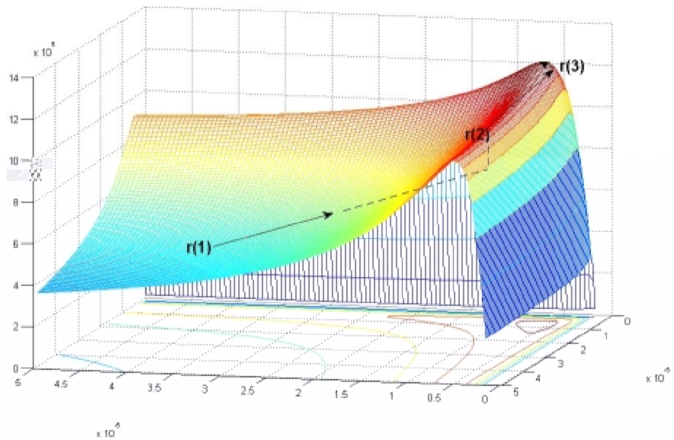
# Algorithm Development-Frequency Selective Channels

- **Binary search assisted ascent (BSAA) for link adaptation in frequency-selective channels**

$$U\left(\left[\mathrm{R}^{[i]} + \mu \nabla U(\mathrm{R}^{[i]})\right]^{+}\right)$$




- **A type of concave fractional programs**
  - **Many standard methods for concave programs can be used**
  - **E.g. Dinkelbach's algorithm (converges superlinearly)**
  - **Details in [Isheden 2011]**

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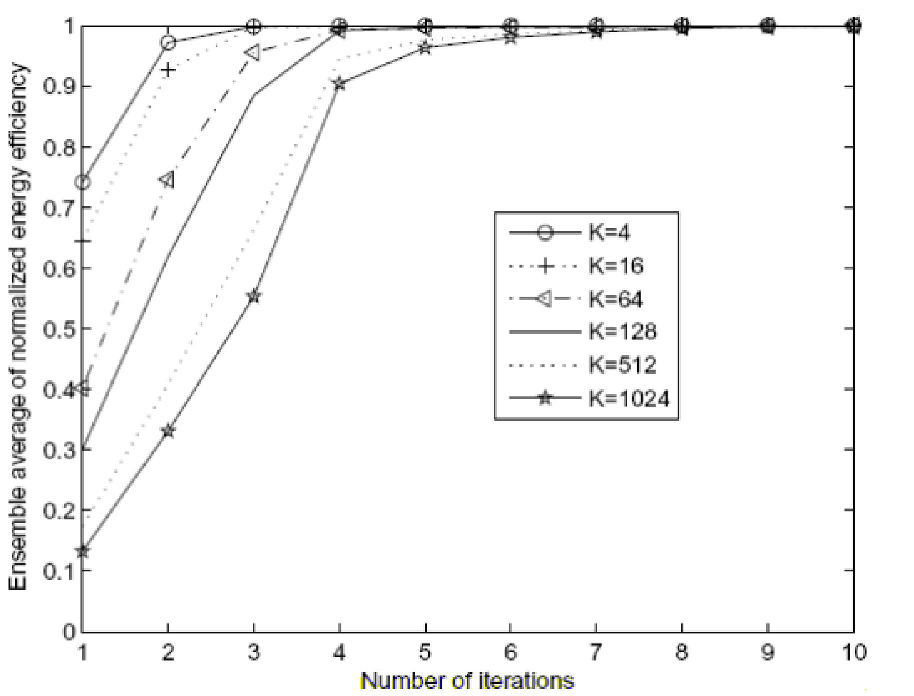
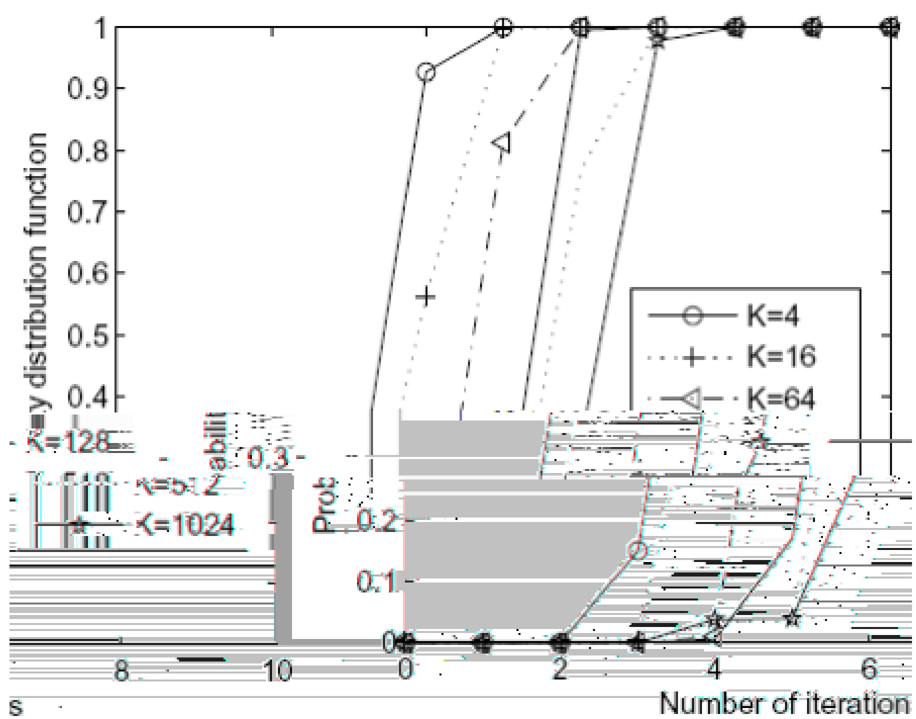
# Convergence of BSAA




Improvement of energy efficiency with iterations.




PDF of # of iterations for convergence

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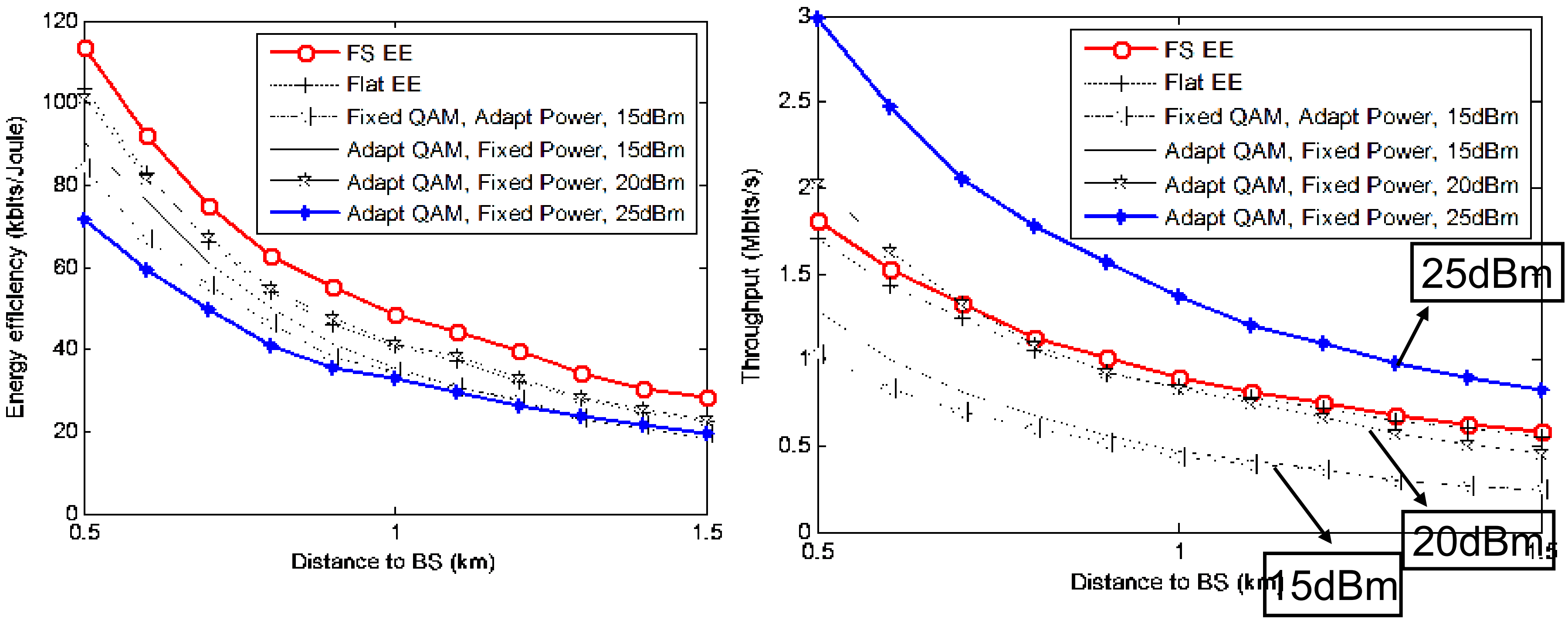
# Performance Comparison




- Energy-efficient link adaptation always achieves the highest energy efficiency
- A tradeoff between energy efficiency and spectral efficiency exists

# Energy Efficiency Metric

- **Exponentially weighted moving average low-pass filters**
  - **Average throughput at time t**

$$T_n[t] = (1 - \frac{1}{w})T_n[t-1] + \frac{1}{w}r_n[t]$$

  - **Average power consumption at time t**

*circuit power*

$$P_n[t] = (1 - \frac{1}{w})P_n[t-1] + \frac{1}{w}(p_n[t] + p_{cn}[t]).$$

overall transmit power on all subchannels

- **Average energy efficiency metric:**

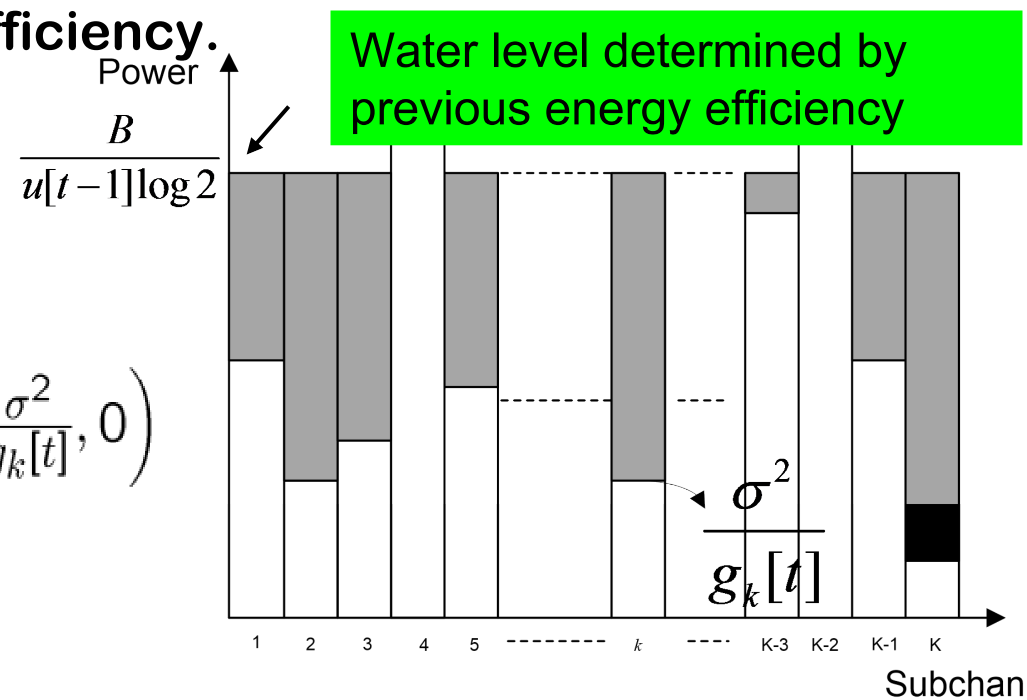
$$u_n[t] = \frac{T_n[t]}{\Delta e / \Delta t} = \frac{T_n[t]}{P_n[t]}$$

## Low-Complexity Energy-Efficient Link Adaptation

- **Note** $w >> 1, u^*[t] \approx u[t-1]$

- **Dynamic water-filling power allocation to the level determined by the previous energy efficiency.**

$$p_k^*[t] = \max\left(\frac{B}{u[t-1]\log 2} - \frac{\sigma^2}{g_k[t]}, 0\right)$$



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# Multi-User Energy Aware Resource Allocation

- In a multi-user system, all subchannels cannot be assigned to one user
- How to assign subchannels?
- Max arithmetic average of energy efficiency (w/o fairness)

$$U[t] = \sum_{n=1}^{N} u_n[t].$$

- Max geometric average of energy efficiency (w/ fairness)

$$V[t] = \sum_{n=1}^{N} \log(u_n[t]).$$

**Energy aware resource allocation based on maximizing network "throughput per joule" metric**

# Resource Allocation w/o Fairness

- Allocation metric:
  - For user n on subchannel k

$$J(n,k) = \frac{r_{nk}[t]}{P_n[t-1]} - u_n[t-1]\frac{p_{nk}[t]}{P_n[t-1]},$$

  - Assign subchannel k to the user with the highest metric

    **Closed-form resource allocation w/o fairness**
  - Circuit power >> transmit power (short distance commun.) and circuit power the same for all users

$$\hat{J}(n,k) \approx r_{nk}[t]$$

Max-SINR scheduler

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# Resource Allocation w/ Fairness

- **Allocation metric:**
  - **For user n on subchannel k**

$$J_f(n,k) = \frac{r_{nk}[t]}{T_n[t-1]} - \frac{p_{nk}[t]}{P_n[t-1]}$$

  - **Assign subchannel k to the user with the highest metric**

    **Closed-form resource allocation w/ fairness**
  - **Circuit power >> Transmit power (short distance commun.)**

$$J_{tf}(n,k) \approx \frac{r_{nk}[t]}{T_n[t-1]}$$

Traditional Proportional
Fair scheduler

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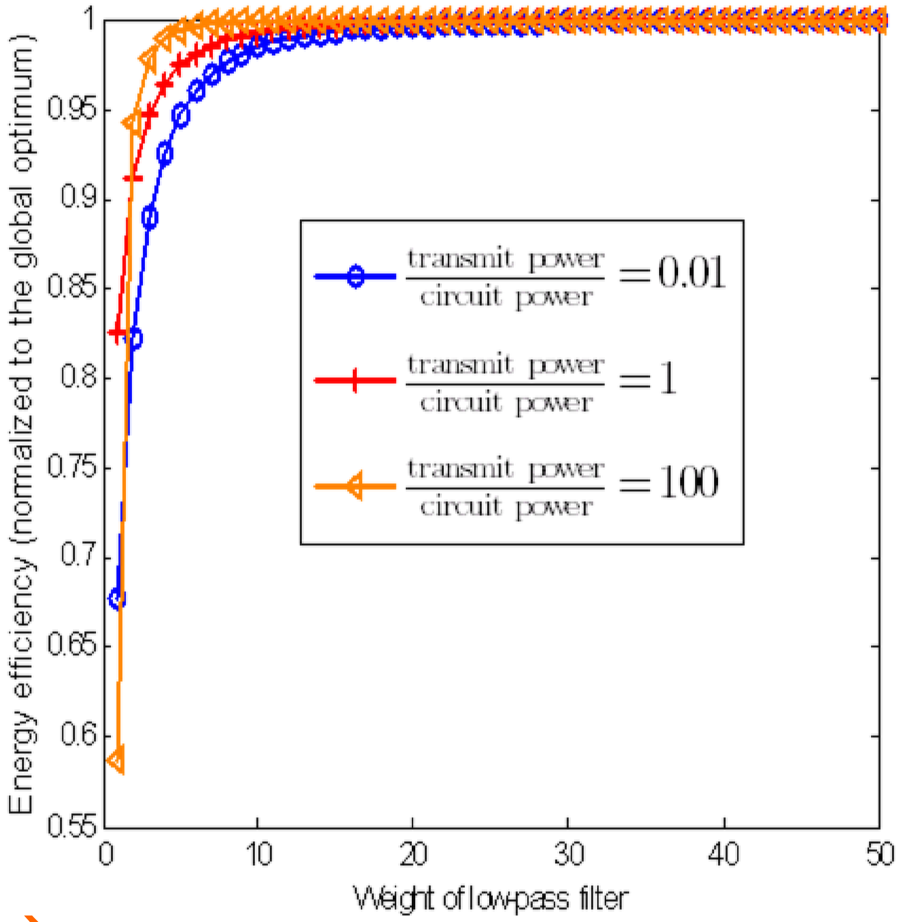
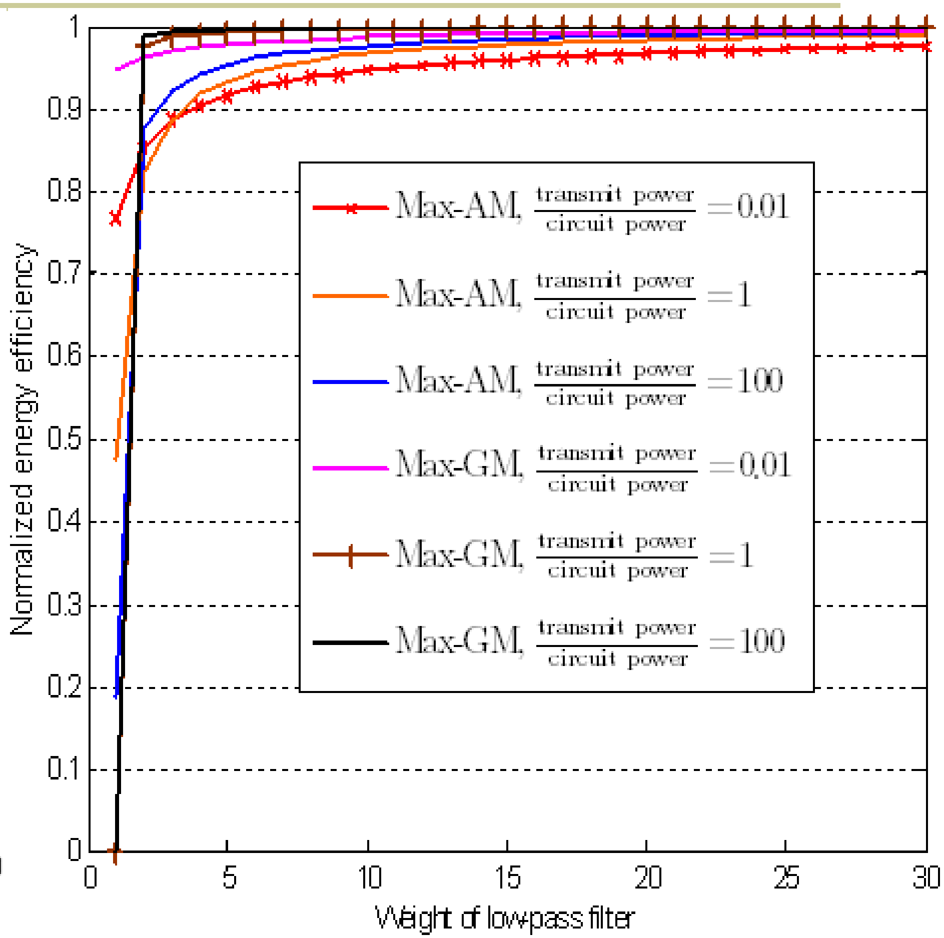
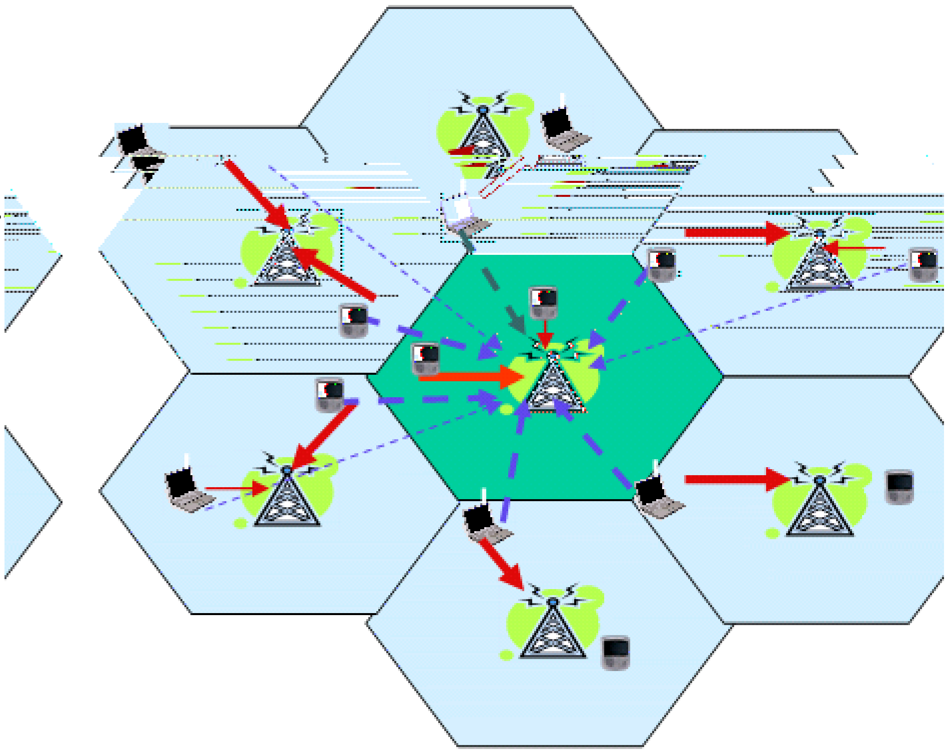
# Performance—Link Adaptation



# Interference-Aware Energy Efficient Communication

- What will happen in a multi-cell **interference-limited** scenario?
- For example: cell-edge users cellular network environment



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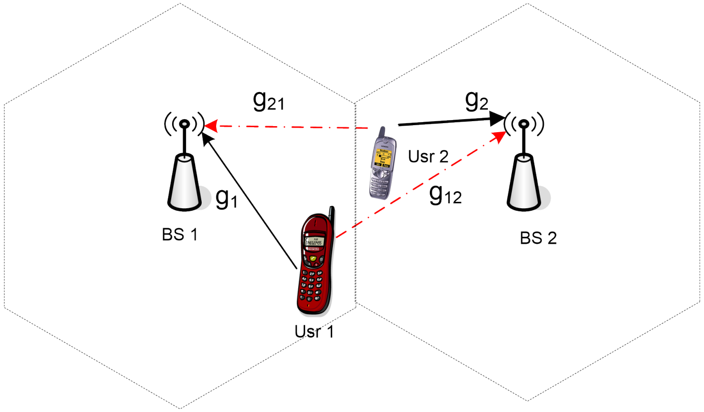
# Two-User Cooperation

- Consider two-user case to obtain insight
  - Users 1 and 2 cooperates to determine their transmit powers
  - Both have complete network knowledge
- Problem modeling

$$u(p_1, p_2) = \frac{\log(1+\dfrac{p_1 g_1}{p_2 g_{21}+\sigma^2})}{p_1+p_c} + \frac{\log(1+\dfrac{p_2 g_2}{p_1 g_{12}+\sigma^2})}{p_2+p_c}$$

- Generally:
  - **Non concave**
  - **Intractable**



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## Cooperative Power Optimization for Special Regimes

**Transmitter condition:**

- 1. circuit power >> transmit power
- 2. transmit power >> circuit power

**Receiver condition:**

- 1. noise power >> interference
- 2. interference >> noise

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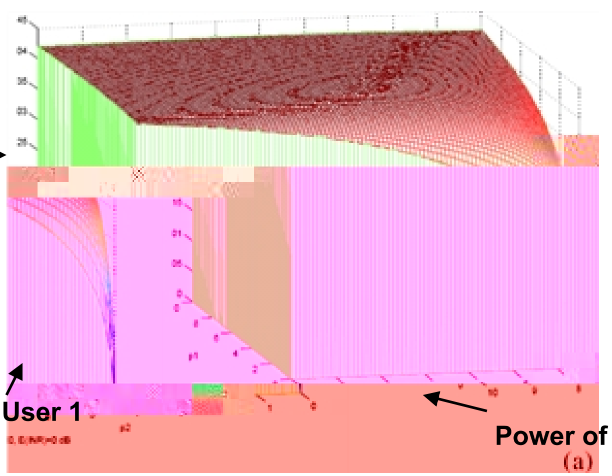
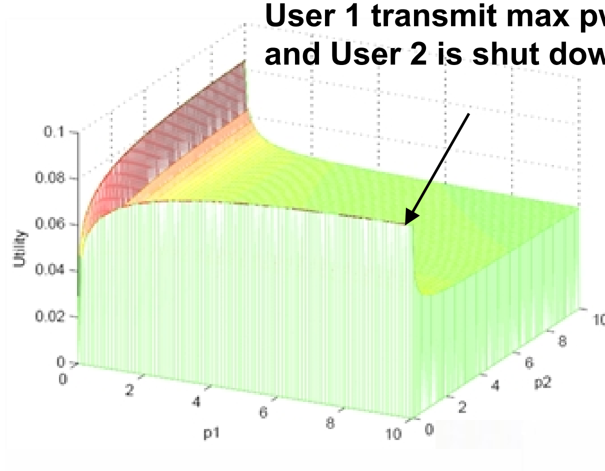
# Circuit Power Dominated Regime

- **When circuit power dominates power consumption**

$$u(p_1,p_2)=\frac{\log(1+\frac{p_1g_1}{p_2g_{21}+\sigma^2})}{p_1+p_c}+\frac{\log(1+\frac{p_2g_2}{p_1g_{12}+\sigma^2})}{p_1+p_c}\approx\frac{\log(1+\frac{p_1g_1}{p_2g_{21}+\sigma^2})+\log(1+\frac{p_2g_2}{p_1g_{12}+\sigma^2})}{p_c}$$

  - Equivalent to throughput optimization
  - Binary power control [Anders 06]




(b) INR=25dB

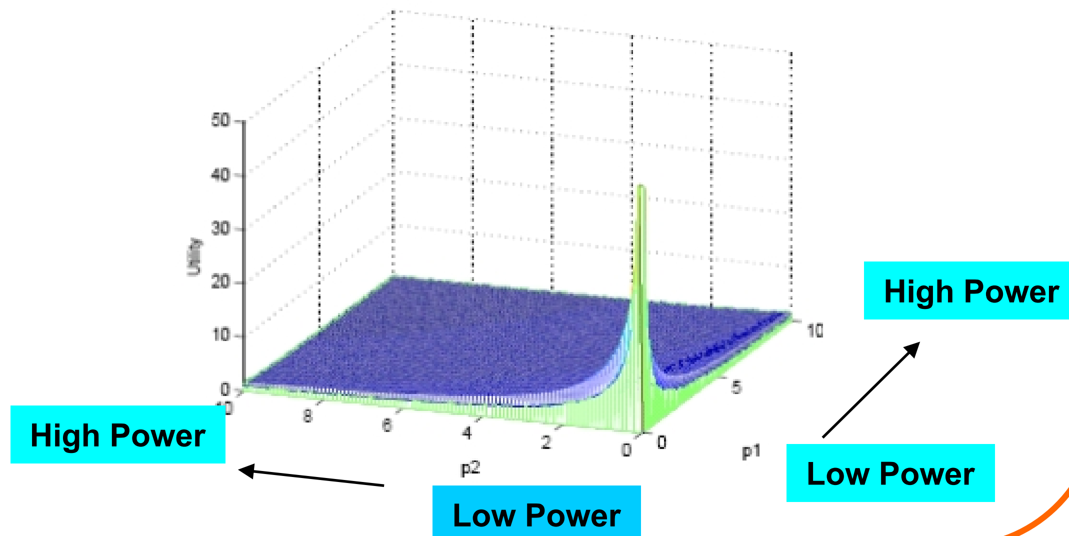
miao@FreeLinguist.com

# Transmit Power Dominated Regime

- When the circuit power is negligible

$$u(p_1,p_2)=\frac{\log(1+\frac{p_1 g_1}{p_2 g_{21}+\sigma^2})}{p_1}+\frac{\log(1+\frac{p_2 g_2}{p_1 g_{12}+\sigma^2})}{p_2}$$

- Users transmit with the lowest power and MCS for maximum energy efficiency [Meshkati06]



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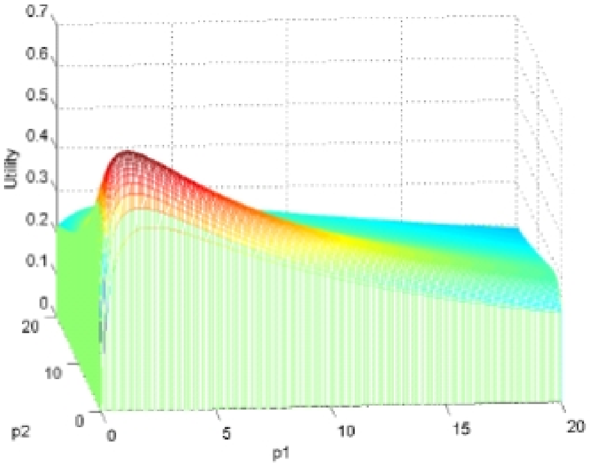
# Noise Dominated Regime

- **When noise power dominates interference plus noise power**

$$u(p_1,p_2)=\frac{\log(1+\frac{p_1 g_1}{\sigma^2})}{p_1+p_c}+\frac{\log(1+\frac{p_2 g_2}{\sigma^2})}{p_2+p_c}$$

- **Interference treated as noise**
- **Independent energy-efficient link adaptation**



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# Interference Dominated Regime

- Interference far larger than noise power

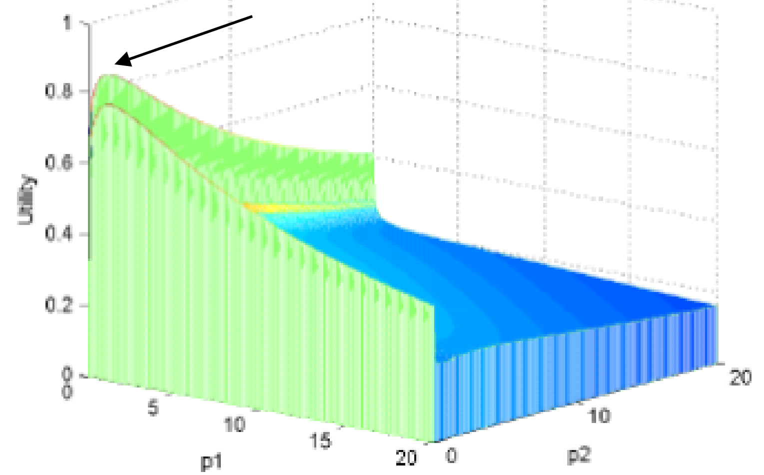
$$\log(1+\frac{p_1 g_1}{}) \qquad \log(1+\frac{p_2 g_2}{})$$

- **On-Off** energy-efficient power control, e.g. time sharing, is optimal

- **Access protocol design is important**
  - Orthogonalize signals of different us
  - SE protocols are also EE
    - DOMRA, CIA-MAC, CAD-MAC

- Link adaptation is different from
- those for SE optimization

Energy-efficient power setting



# Intractability for General Cases

- What's the situation for normal regimes?
  - Non-concavity
  - Multiple local maximums
  - Behaviors of local maximums hard to predict
- Multiple subchannels and users further complicate the problem
- Impractical — complete network knowledge
- What can we do?

Non-cooperative

# Non-Cooperative Energy-Efficient Power Optimization

- **User $n$ chooses power to selfishly optimize energy efficiency**

$$\mathbf{P}_n^o = f_n(\mathbf{P}_{-n}) = \arg\max_{\mathbf{P}_n} u_n(\mathbf{P}_n, \mathbf{P}_{-n}).$$

  - **Note: not appropriate for throughput, i.e. SE, maximization**
    - **1). Aggressive power control: selfish users increase transmit power beyond what is reasonable [Goodman 2000]**
    - **2). Pricing is needed to regulate the aggressive behaviors [Gesbert2007]**

- **Observation:**

$$\mathbf{P}_n^o = \arg\max_{\mathbf{P}_n} \log(u_n(\mathbf{P}_n, \mathbf{P}_{-n})) = \arg\max_{\mathbf{P}_n} \left(\overbrace{\log(r_n)}^{\text{SE optimal}} - \overbrace{\log(P_n + P_c)}^{\text{Power pricing}}\right),$$

  - **A variation of traditional spectral-efficient power control with power pricing**

Non-cooperative energy-efficient power control is desirable to reduce interference and improve throughput in a non-cooperative setting.

miao@FreeLinguist.com

# Properties of Equilibrium

- **Equilibrium:**
  - The condition that competing influences are balanced
  - Its properties are important to network performance

- **We analytically show:**
  - The equilibrium always exist;
  - Necessary and sufficient conditions of the equilibrium
  - With flat fading channels, the equilibrium is unique, regardless of network conditions (channel gains, user distribution)
  - With frequency-selective channels, the number of equilibrium depends on interference channel gains

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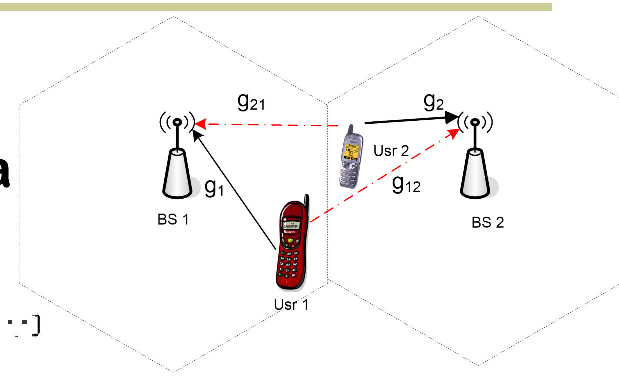
# Equilibrium in Frequency-Selective Channels

- In frequency-selective channels,
  - An example with at least two equilibria




[illegible]

[illegible]

- One equilibrium:

$$\mathbf{p}_1^* = [p_a, p_b]^T \text{ and } \mathbf{p}_2^* = [p_c, 0]^T$$

- Another due to symmetry of network assumptions

$$\mathbf{p}_1 = [p_c 0]^T \text{ and } \mathbf{p}_2 = [p_a p_b]^T$$

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# Equilibrium in Frequency-Selective Channels

- **Sufficient conditions** **to assure** **a unique equilibrium**

$$||f_n(\mathbf{p}_{-n}) - f_n(\check{\mathbf{p}}_{-n})|| < ||\mathbf{p}_{-n} - \check{\mathbf{p}}_{-n}||$$

or

$$\left|\left|\frac{\partial \mathbf{I}_n}{\partial \mathbf{p}_{-n}}\right|\right| < \frac{1}{\text{sup}_{\mathbf{I}_n}\left|\left|\frac{\partial f_n}{\partial \mathbf{I}_n}\right|\right|}$$

only depend on interference channel gains

independent of interference channel gains

$$\frac{\partial \mathbf{I}_n}{\partial \mathbf{p}_{-n}} = \begin{pmatrix} g_{1n}^{(1)} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & g_{1n}^{(K)} \\ & \vdots & \\ g_{(n-1)n}^{(1)} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & g_{(n-1)n}^{(K)} \\ g_{(n+1)n}^{(1)} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & g_{(n+1)n}^{(K)} \\ & \vdots & \\ g_{Nn}^{(1)} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & g_{Nn}^{(K)} \end{pmatrix}$$

**where $||A||$ is the Frobenius norm of $A$.**

  - **Not necessary: flat-fading channel cases**

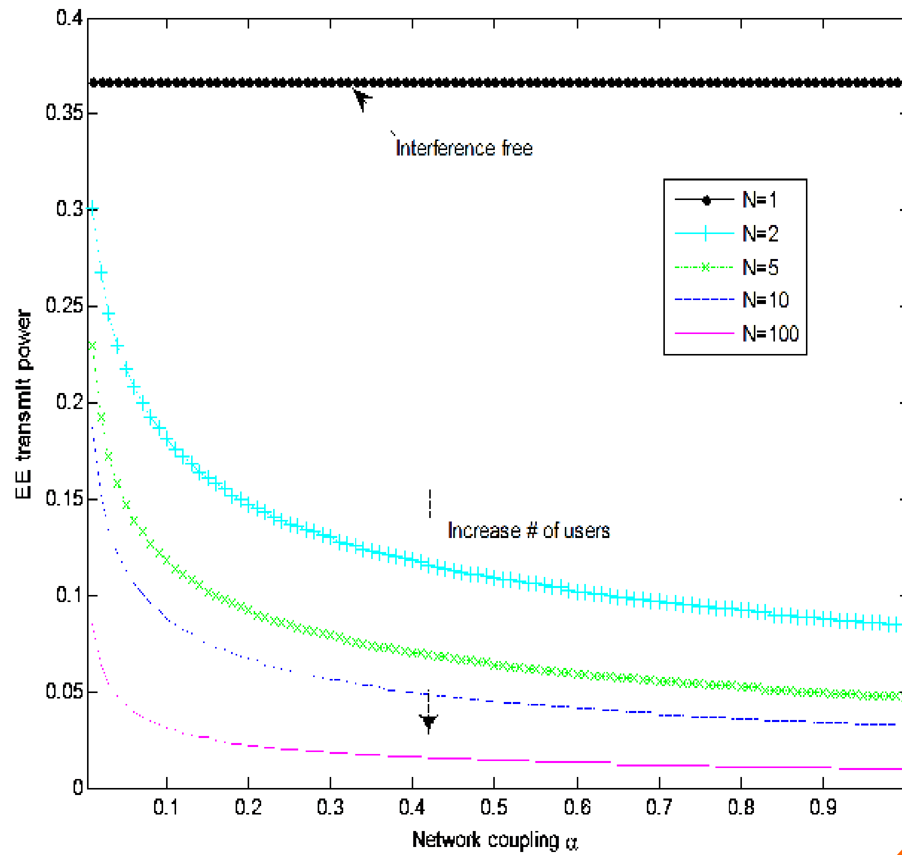
miao@FreeLinguist.com

# Equilibrium Power

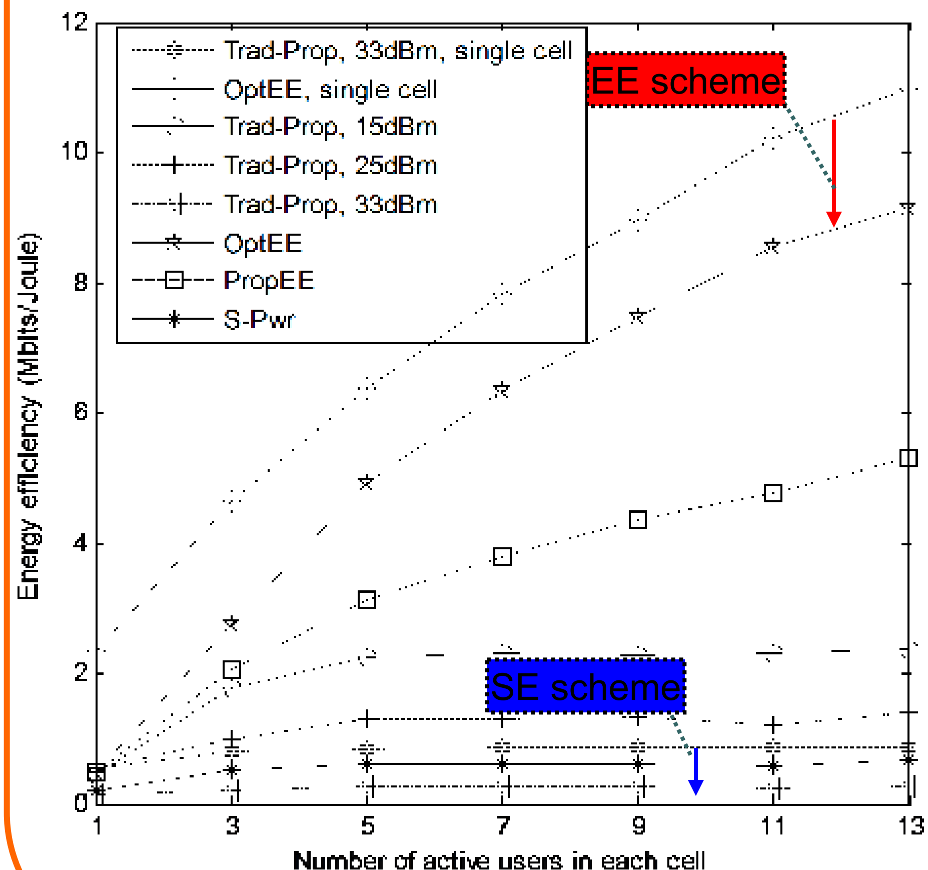
- **Define Network coupling factor**

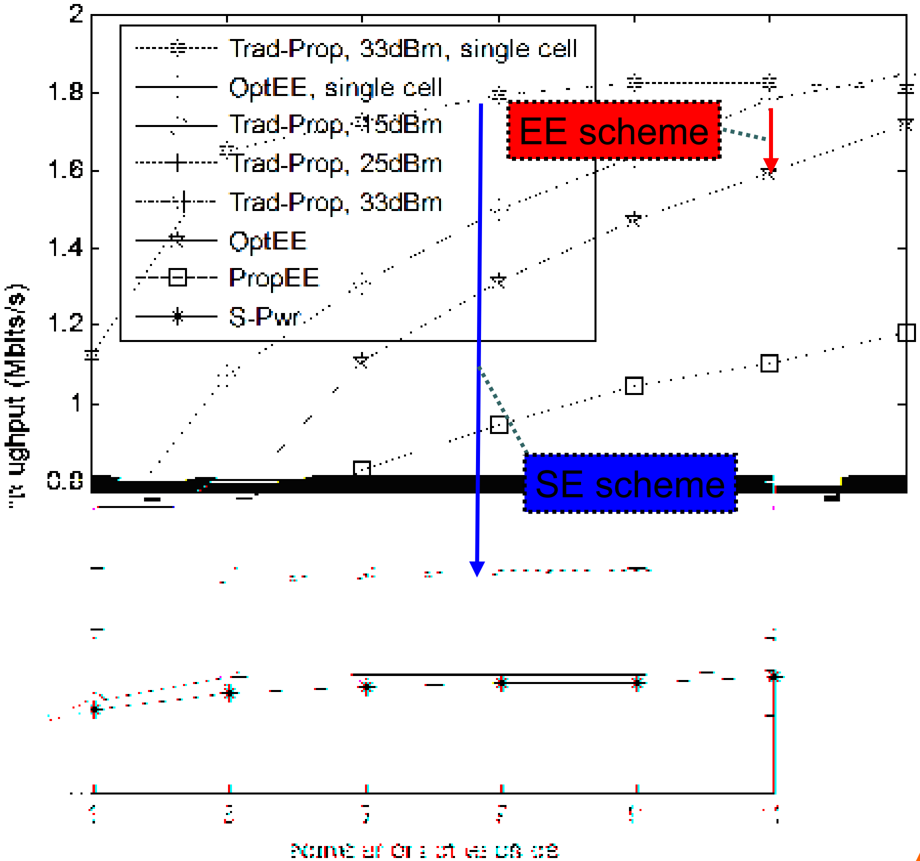
$$\alpha = \frac{\text{average intference path gain}}{\text{average signal path gain}}$$

- **Characterizes what level different transmissions interfere with each other**
- **Eqiulibrium power adapts to interference strength: stronger intf., lower pwr**



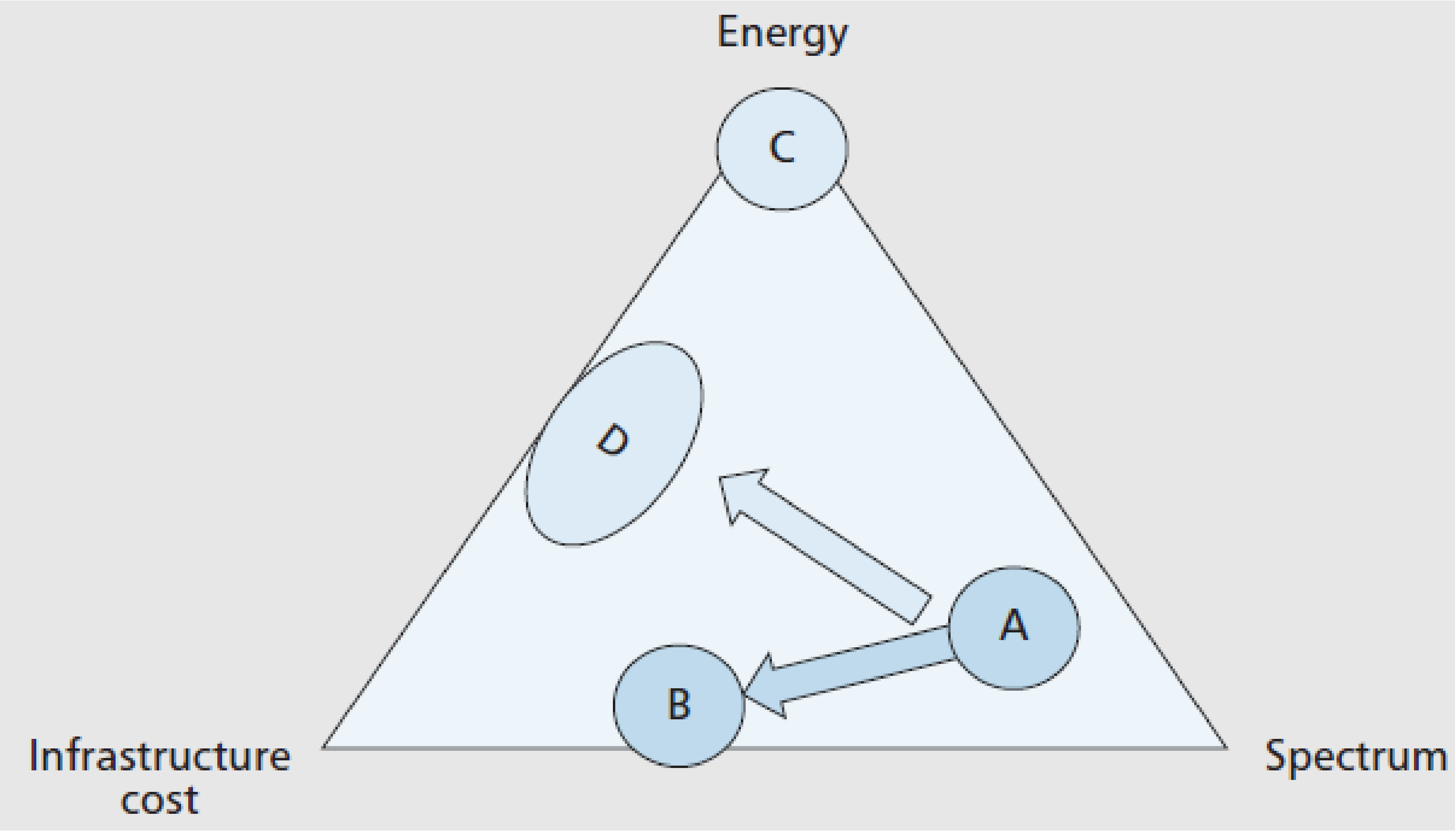
# Performance in a 7-Cell Cellular Network



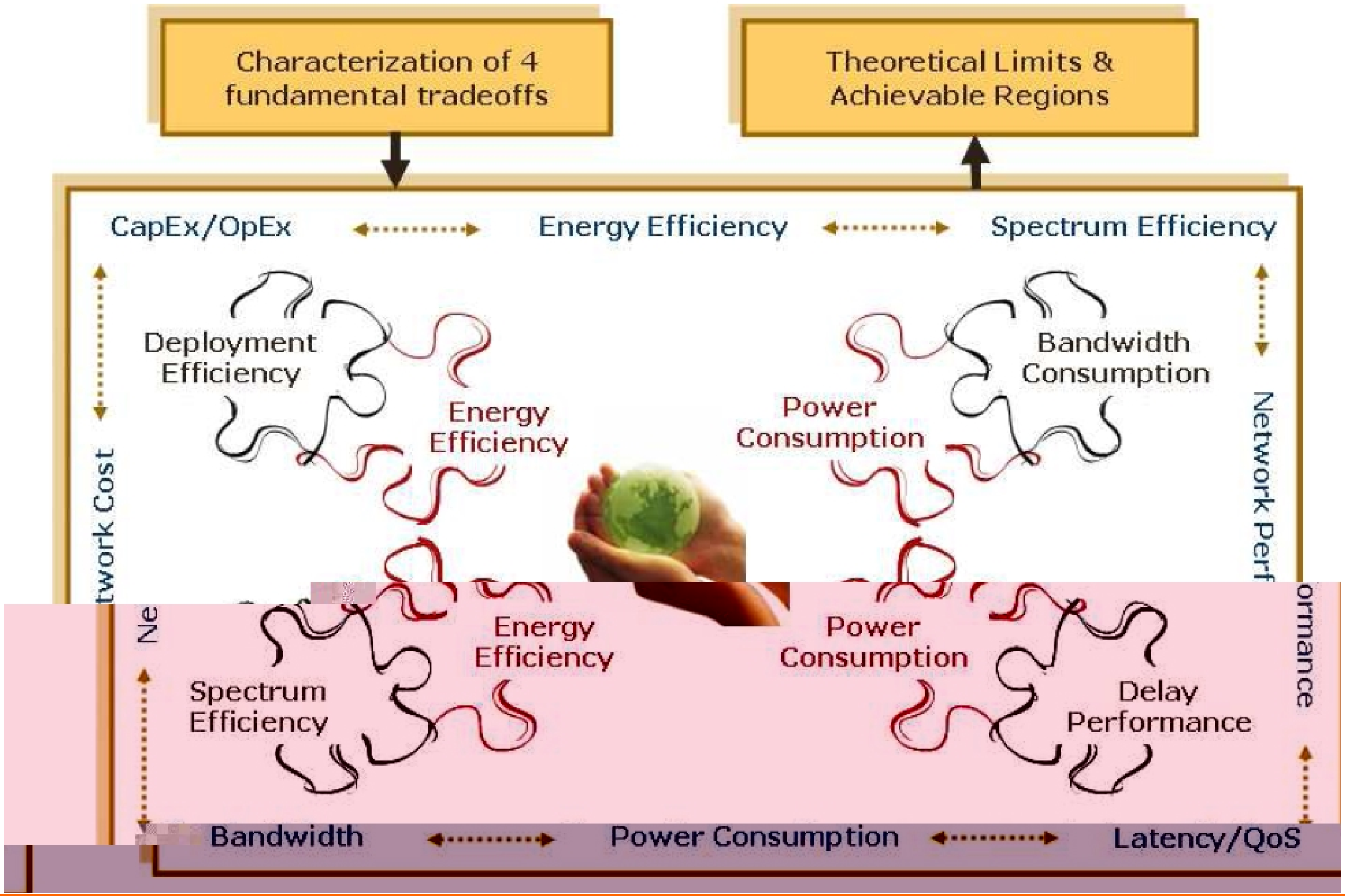
# 6. Energy-Efficient Mobile Access Networks: A Tradeoff Perspective

# Key Design Constraints




Tombaz, A. Västberg and J. Zander, Energy and Cost Efficient Ultra High Capacity Wireless Access", IEEE Wireless Communication Magazine, vol. 18, no. 5, pp. 18- 24, October 2011.

# Tradeoffs in Cellular Network Design



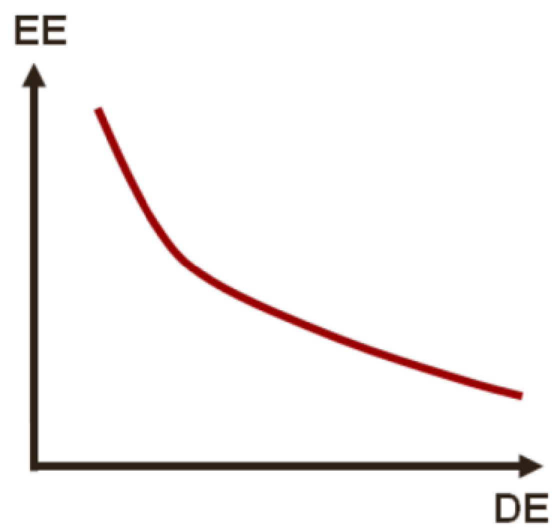
# DE – EE

- DE: a measure of system throughput per unit of deployment cost
  - An important network performance indicator for mobile operators.

- DE consists of
  - Capital expenditure (CapEx)
    - Infrastructure costs (base station equipment, backhaul transmission equipment, site installation, and radio network controller equipment.)
  - Operational expenditure (OpEx)
    - electricity bill, site and backhaul lease, and operation and maintenance cost

# Conflicting Design Rules

- **DE:**
  - **Large cell radius to save expenditure on site rental, base station equipment, and maintenance, etc.**
- **EE:**
  - **Smaller cell radius to save transmit power**
  - **Example [Badic 2009]:**
    - **By shrinking the cell radius from 1, 000 m to 250 m, the maximum EE of the HSDPA Network will be increased from 0.11 Mbits/Joule to 1.92 Mbits/Joule, respectively**



# Some Practical Considerations

- **Previous DE-EE tradeoff assumes**
  - **deployment cost scales continuously and proportionally with the cell radius.**
  - **only transmit power**
- **In reality**
  - **the equipment cost does not scale proportionally with the target cell size;**
  - **the total network energy includes both transmit-dependent energy (e.g. power consumed by radio amplifier) and transmit-independent one (e.g. site cooling power consumption).**
- **The relation of DE and EE may deviate from the simple tradeoff curve and become more complex when considering practical aspect**

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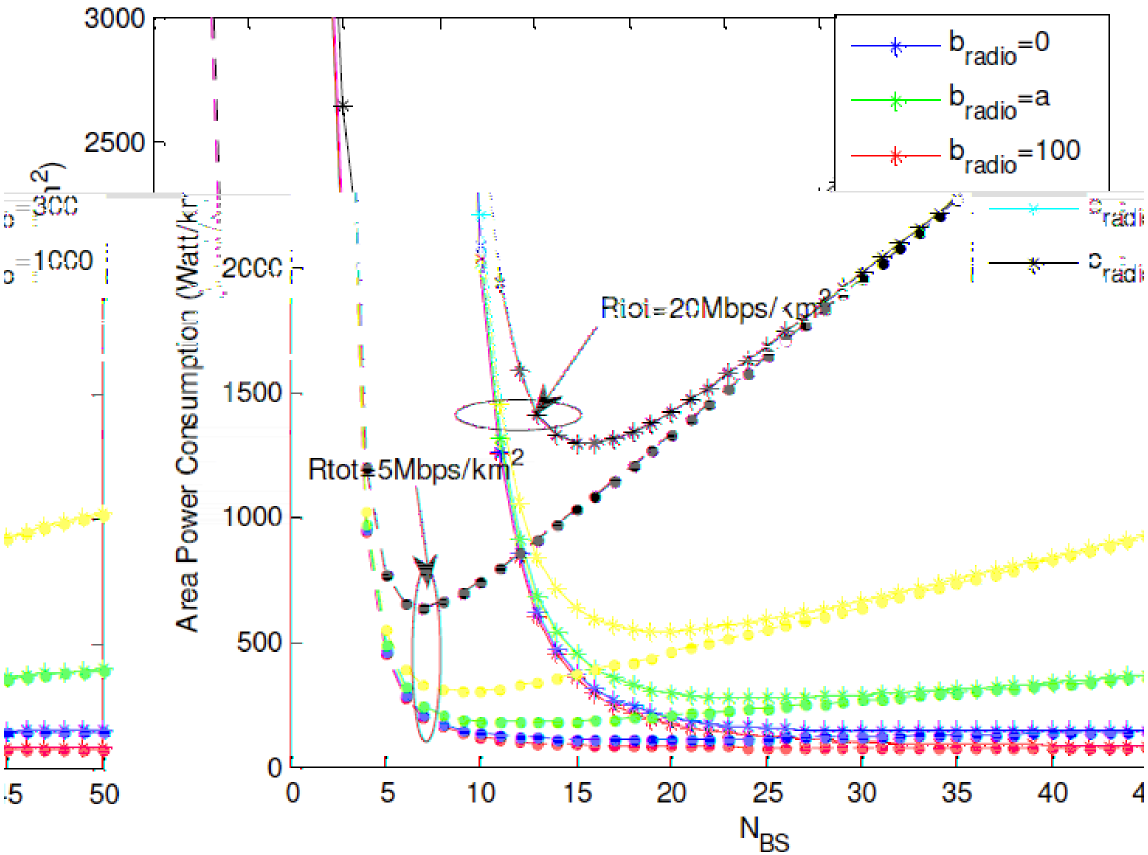
# Area Power Consumption and BS Density



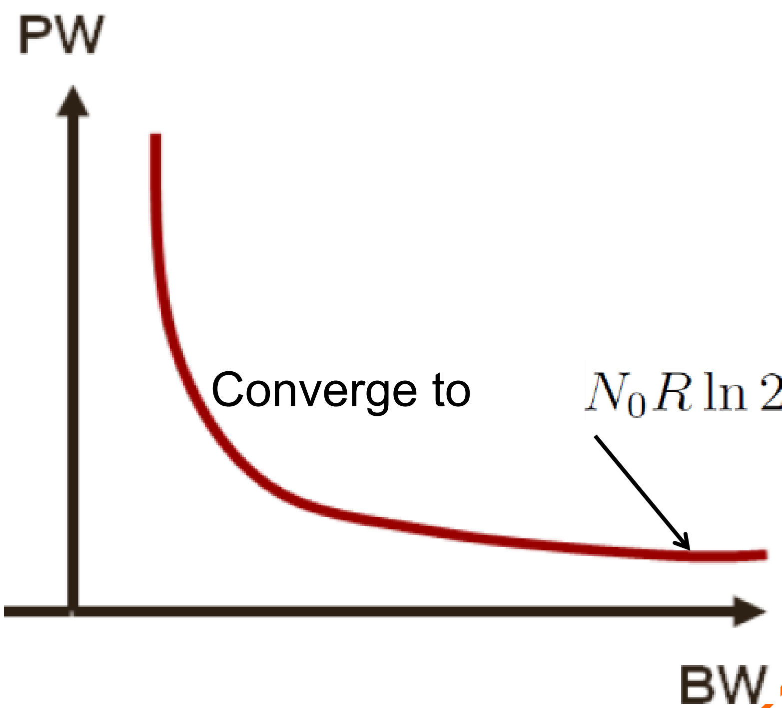

Tombaz, A. Västberg and J. Zander, Energy and Cost Efficient Ultra High Capacity Wireless Access", IEEE Wireless Communication Magazine, vol. 18, no. 5, pp. 18- 24, October 2011.

miao@FreeLinguist.com

# BW-PW

- **Given a data transmission rate**
  - **Expansion of signal bandwidth reduces transmit power and achieves better energy efficiency.**

$$P = WN_o(2^{\frac{R}{W}} - 1)$$



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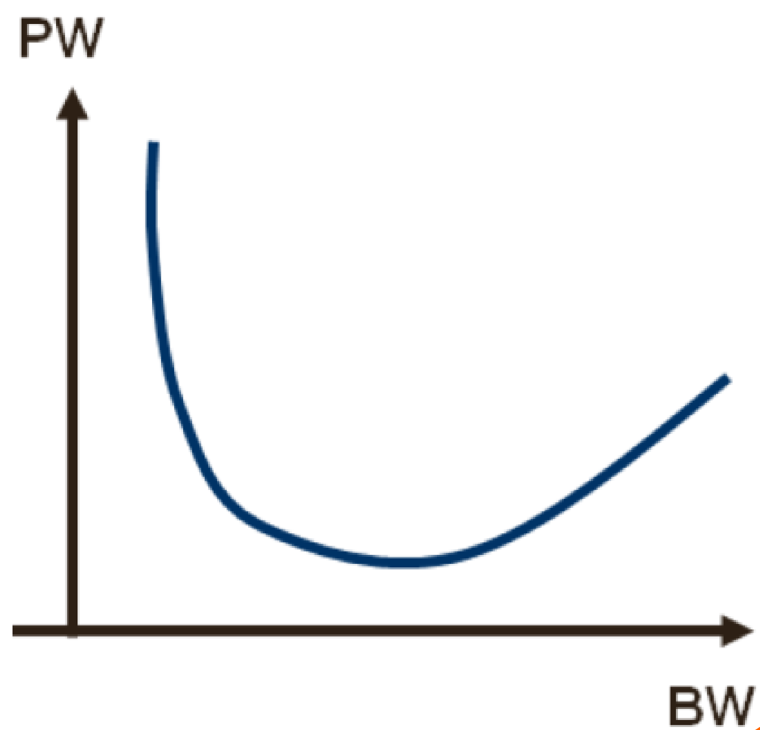
# BW-PW: In Practice

- Given a data transmission rate
  
  Expansion of signal bandwidth reduces transmit power and achieves better energy efficiency.

- In practice:
  - the circuit power consumption, such as filter loss, actually increases with the system BW



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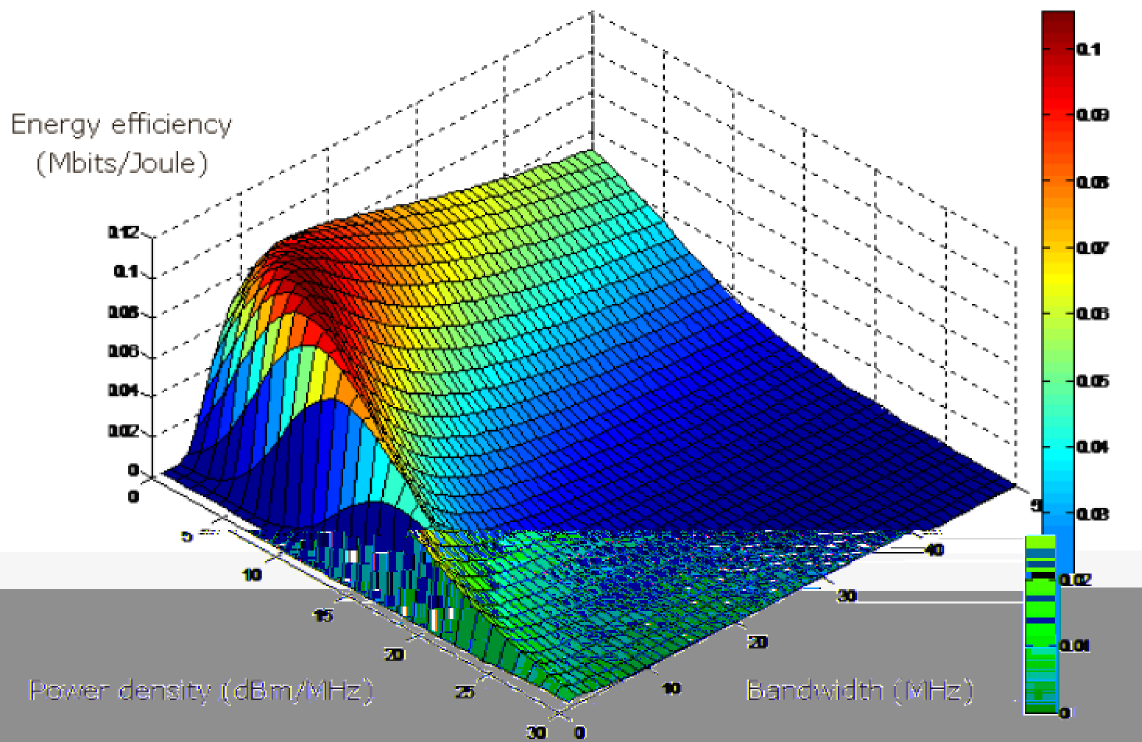
# Circuit PW Scales with Bandwidth

- Curves of BW-PW-EE Relations




- Full utilization of bandwidth-power resource may not be most energy efficient
- Given target EE, the BW-PW tradeoff relation is not monotonic

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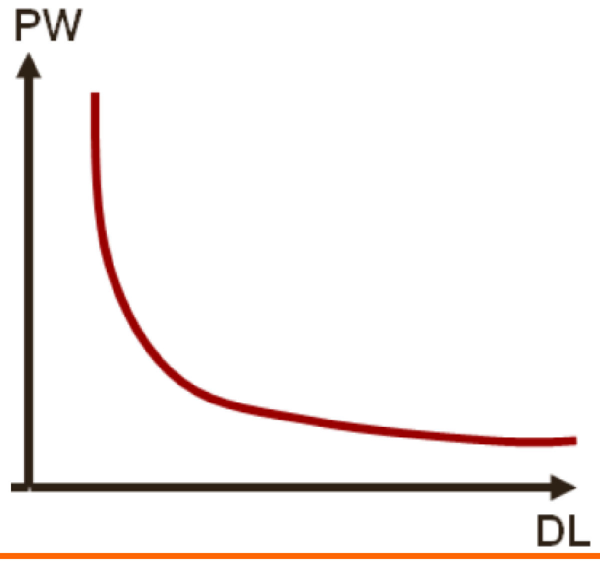
# DL-PW

- **According to Shannon:**

$$P_b = W N_o t_b \left(2^{\frac{1}{t_b W}} - 1\right)$$

**Time needed for sending one bit, i.e. delay**

**Power needed for reliable delivery of one bit**



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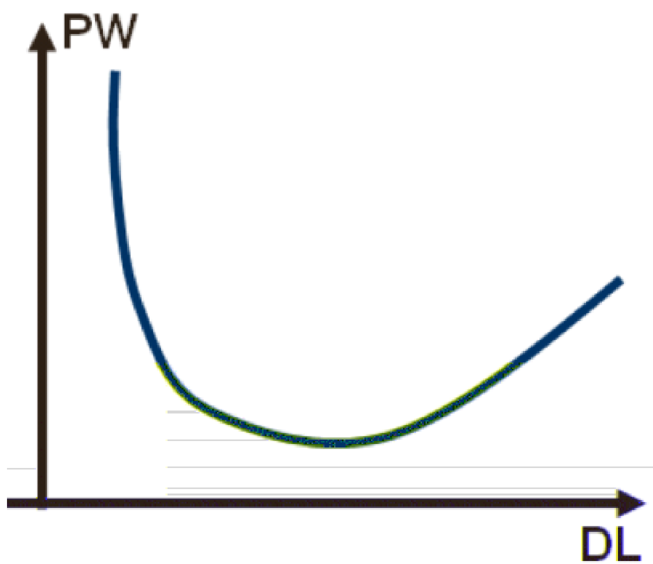
# DL-PW: In Practice

- **Other device power needed to enable operation:**

$$P_b = WN_o t_b (2^{\frac{1}{t_b W}} - 1) + F(t_b)$$

**Other device power**



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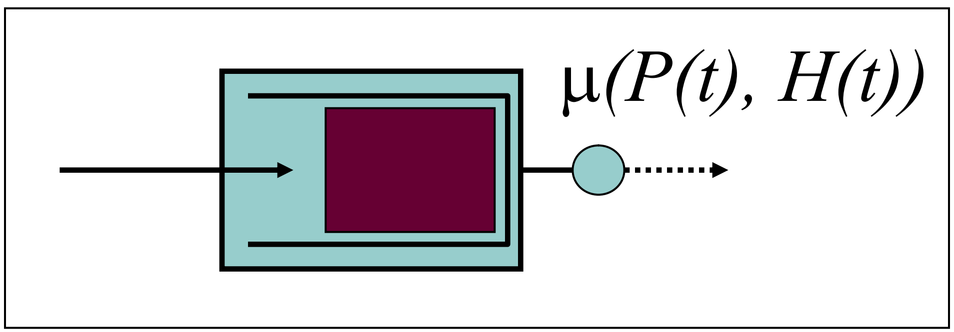
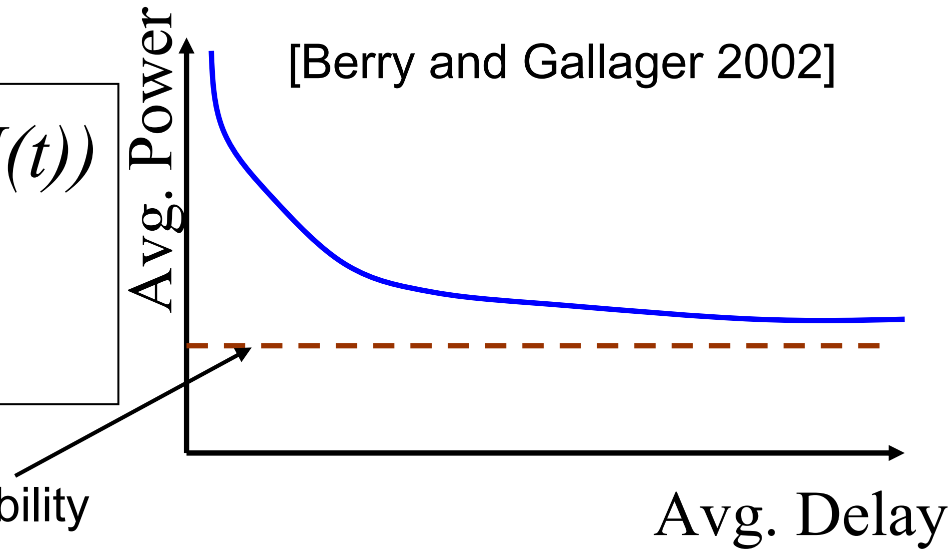
# DL-PW: One Step Further

- **Traffic dynamics**
  - **Delay include both the waiting time in the traffic queue and the time for transmission**



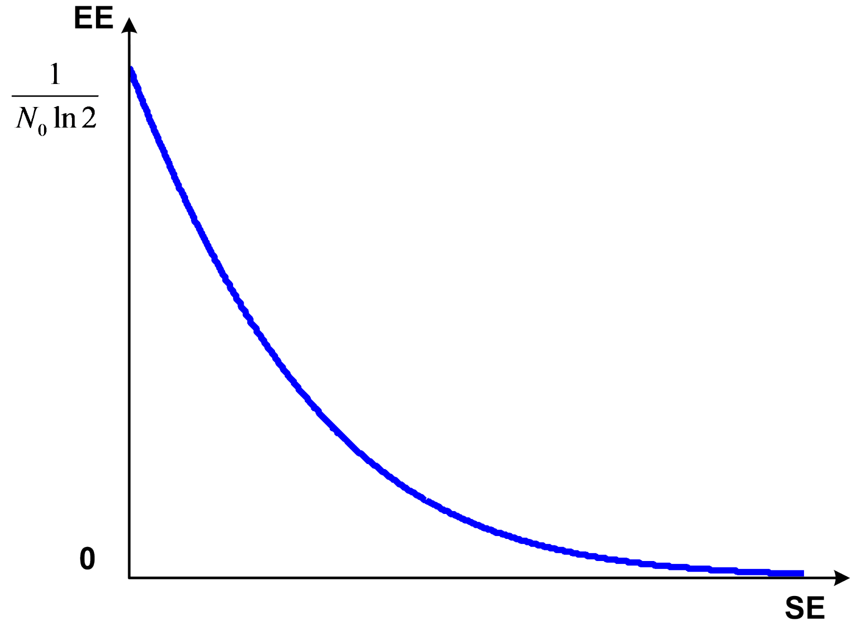




**Open problem with practical considerations**

# SE-EE

- **In single-user scenario**
  - **SE** $$\eta_{SE} = \log_2(1+\frac{P}{WN_0})$$
  - **EE** $$\eta_{EE} = \frac{W\log_2(1+\frac{P}{WN_0})}{P}$$
  - **SE-EE relationship**

$$\eta_{EE} = \frac{\eta_{SE}}{(2^{\eta_{SE}}-1)N_0}$$



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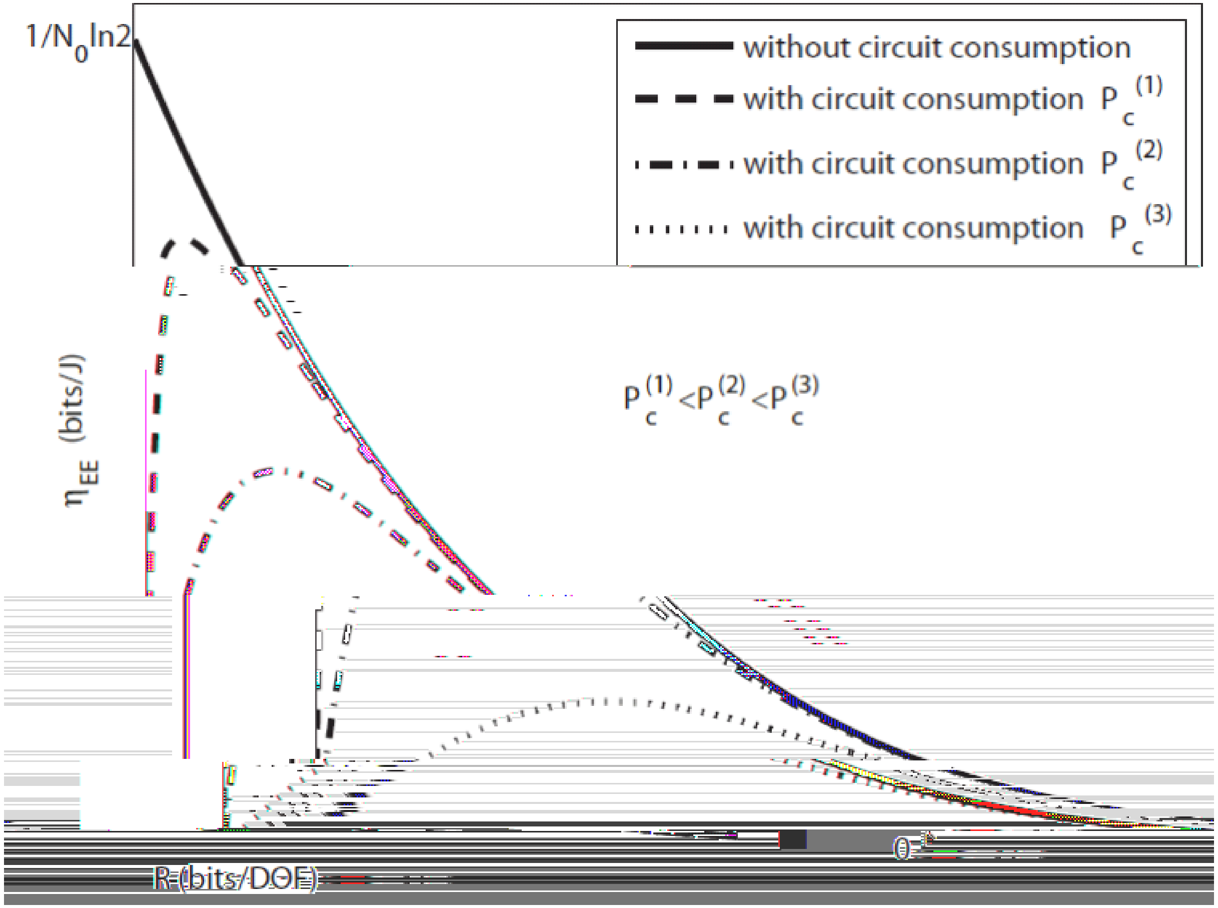
# SE-EE In Practice

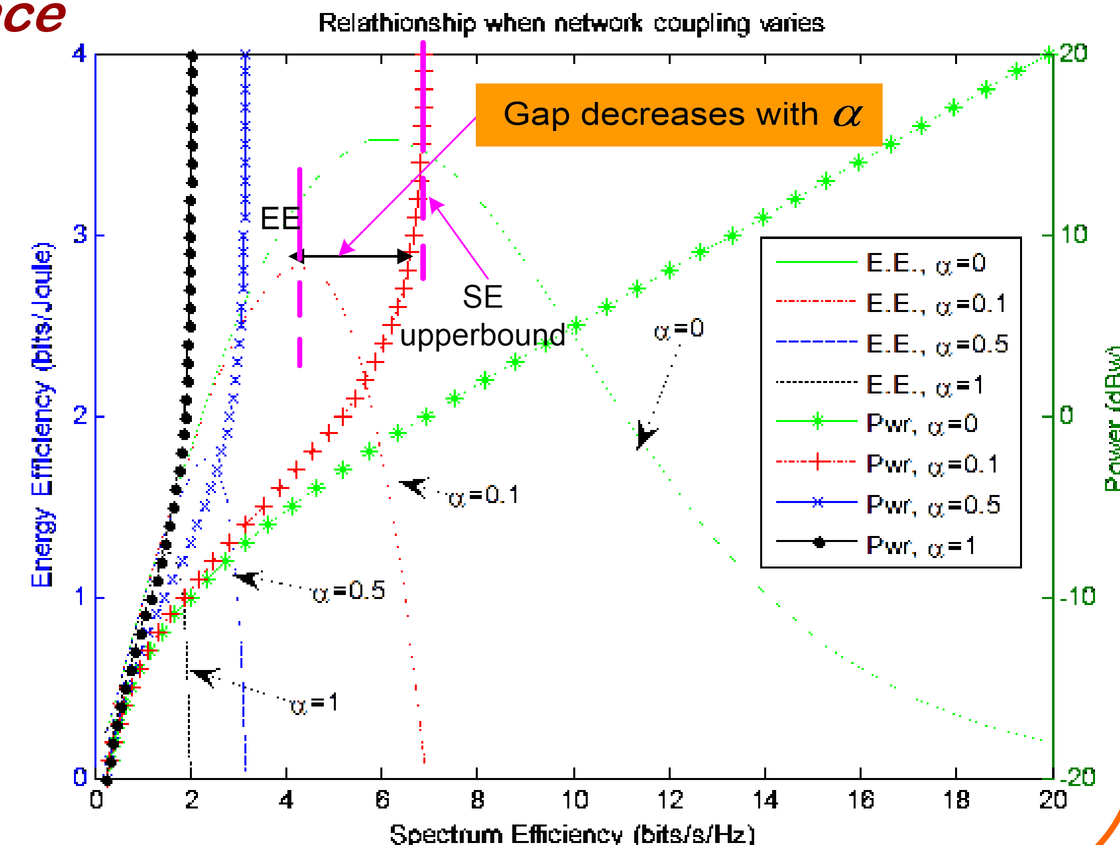


# SE-EE: In Practice

- ***Reduced tradeoff between energy efficiency and spectral efficiency w/ interference***

*Interference bounds SE*

*EE is sensitive to pwr, but SE is not .*



# 7. CONCLUSIONS AN REFERENCES

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# Conclusion

- Cross-layer optimization for SE
  - Spectral-efficient link adaptation
  - Spectral-efficient centralized MAC
  - Spectral-efficient distributed MAC
- Cross-layer optimization for EE
  - Energy-efficient link adaptation
  - Energy-efficient centralized MAC
  - Energy-efficient distributed MAC
- Energy-Efficient Mobile Access Networks: A Tradeoff Perspective

miao@FreeLinguist.com

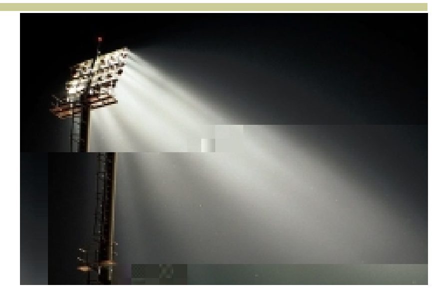
# Light Analogy

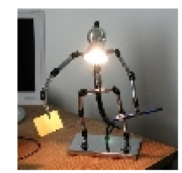
Oil lamp ( first mass produced)

(1G?)

Gas lights

(2G?)





Electrical lamps

(3G and beyond?)

Brighter and brighter …
(Higher and higher lumen capacity)
And ……

A

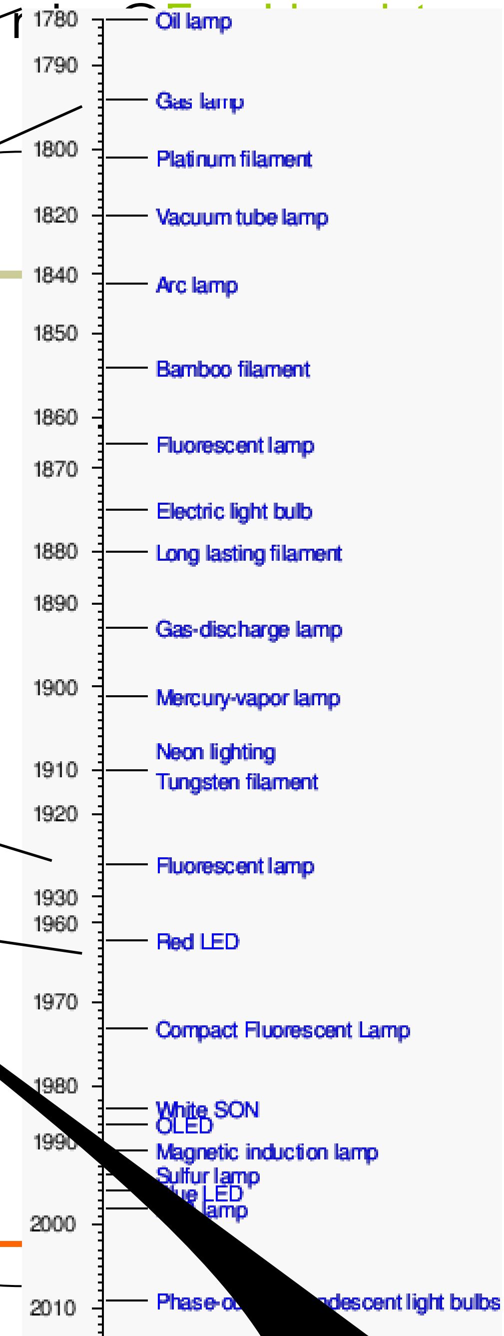
# Light Analogy

1780, oil lamp

1794, gas lamp

From 1800, electric lamp

**1926, fluorescent lamp**
**(1/5 energy consumption, 5 years life)**



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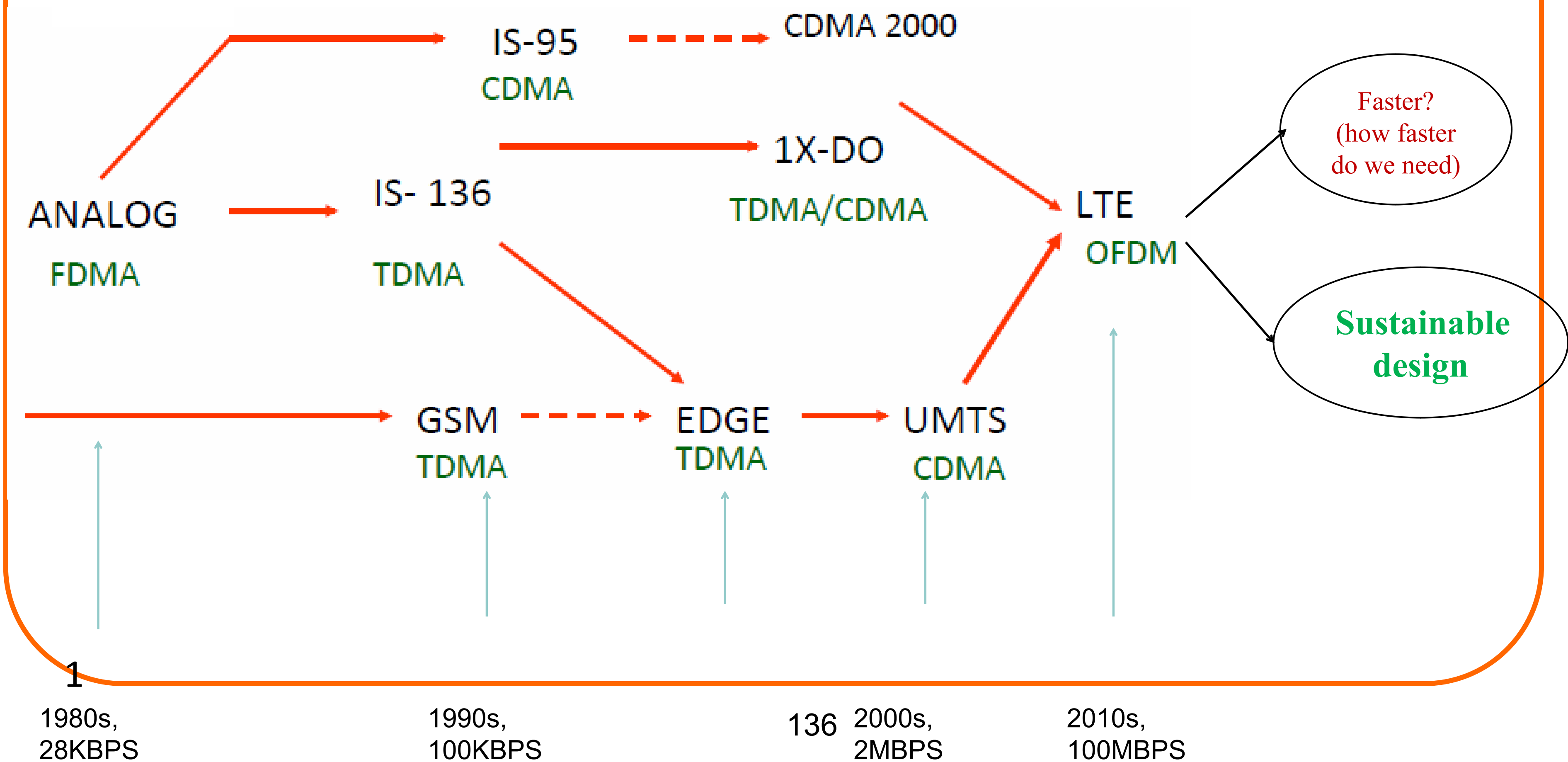
# Implications ....

- **Where are we?**



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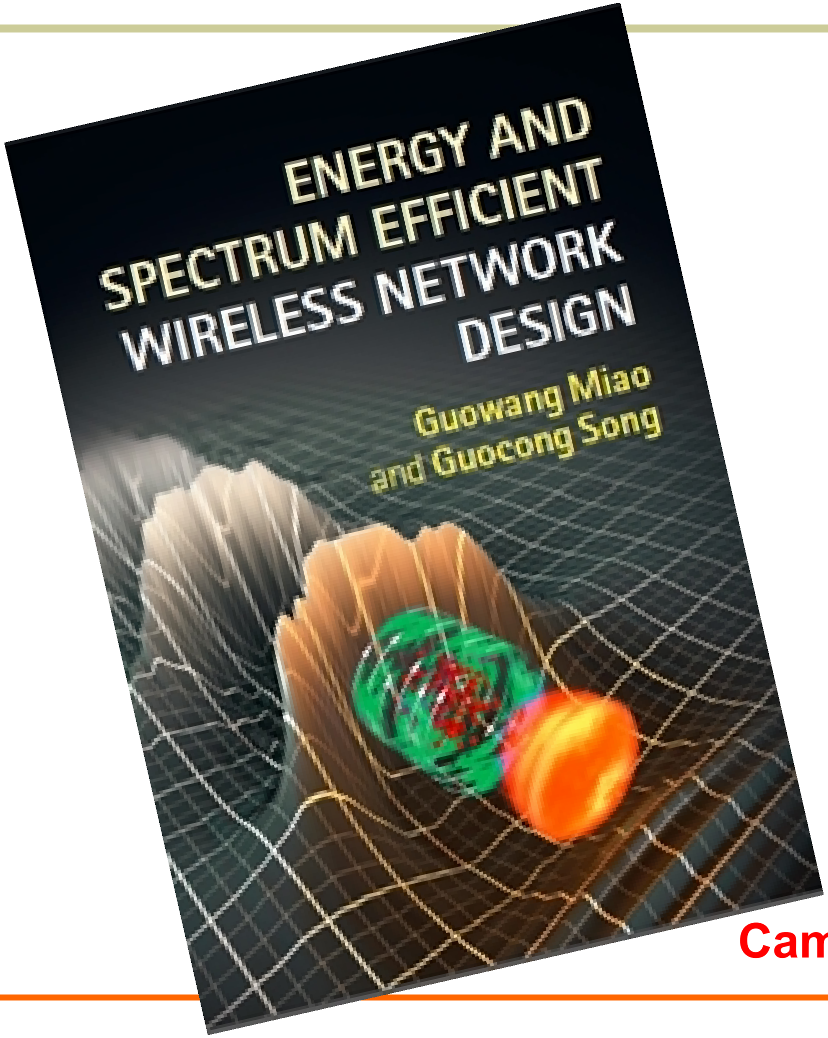
# More Information

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# REVOLUTIONAL THINKING AHEAD

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- Numerous slides and other resources publicly available on the Internet

# Q&A