Increasing Wireless Data Throughput by Orders of Magnitude

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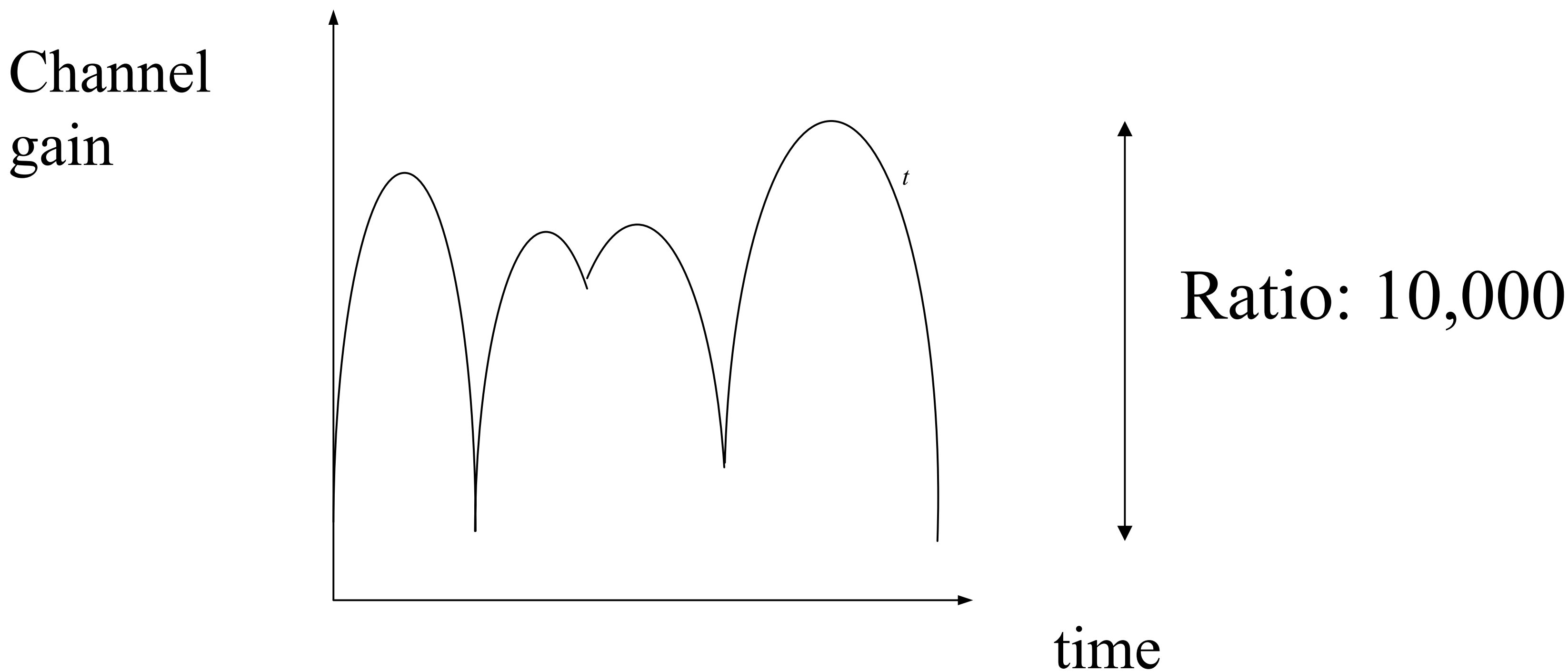
General Motivation

- Wireless communication is limited by precious radio spectrum and power.
- We want to have efficient use of them maximize the data transfer rate.

Observation

- The condition of wireless links can change very quickly; “fading”.
  - Due to motion



e.g.,

1.5 GHz carrier
36 Km/hour = 10 m/sec
$1/(2f_D)$ = 10 msec

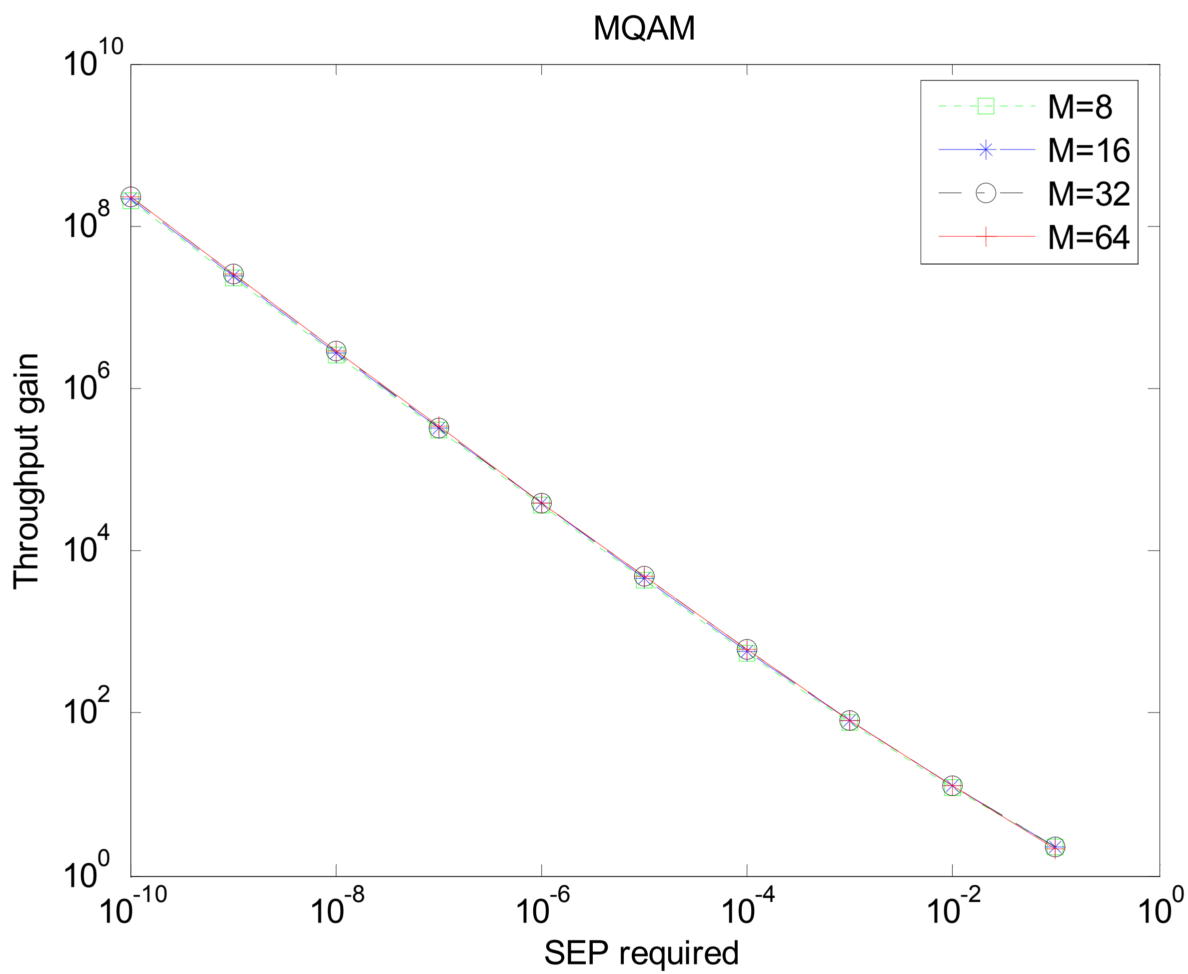
Basics

- For the same fidelity requirement
  - At good condition: we can send data at high rate
  - At bad condition: we should slow down

Core Idea of Technology

- If the channel condition changes very quickly, we adapt the data transmission rate that quickly.
  - Current systems adapt slowly.
- Rapid adaptation can increase the average data rate 10,000 times!!!!

Bit (symbol)-error constrained throughput gain



Unique features

- Why can't current system do it?
  - Receiver must know the rate at which data are transmitted.
  - In current systems, sender explicitly tells the receiver the rate information. (frame-by-frame adaptation)
- Our idea
  - Sender changes the data rate symbol-by-symbol (much smaller unit than frame)
  - Sender does not tell the receiver the rate information
  - Receiver figures out the data rate.

How?

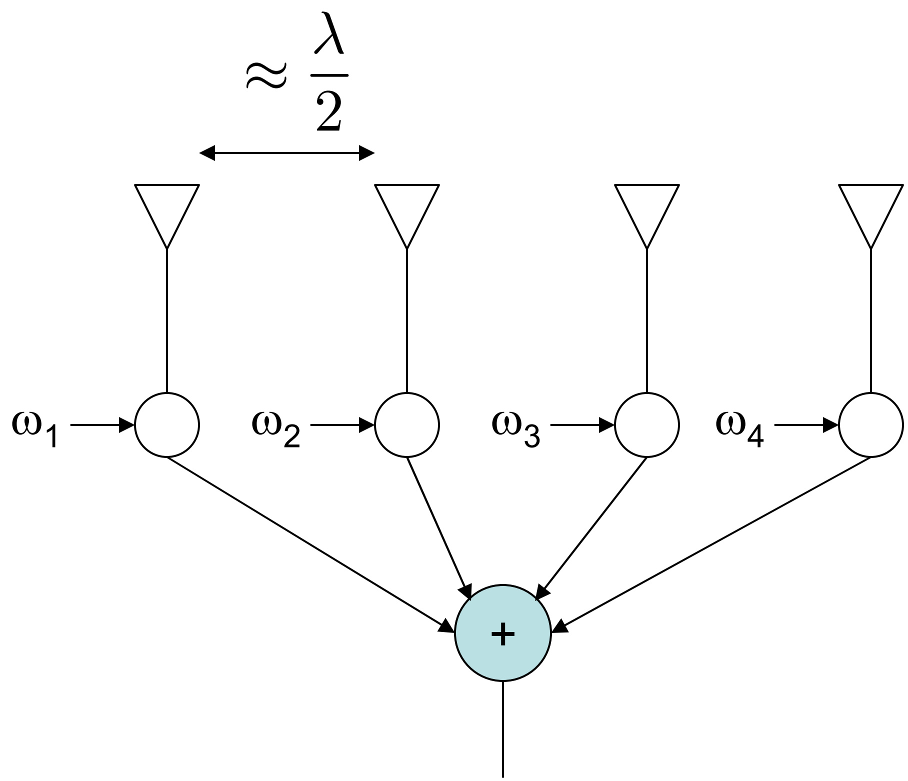
- Clever design and use of sequences modulating the transmitted signal
- “Sequence” idea is congenial to CDMA (Code Division Multiple Access) – 3G cellular
  - Thus, easily integrated to 3G cellular systems

Competing Technologies

- Other methods of increasing average data rate
  - Diversity combining
  - Bit interleaving and forward error correction

Combating fading

- E.g., Space diversity



Maximal Ratio Combining

Good news

- They are also complementing technology
  - Can put together diversity combining, bit interleaving, error correction code, and our scheme to maximize the performance.
  - Our adaptation scheme can increase the average data rate even further from other schemes

State of Tech.

- Research stage, but ready to build a prototype
  - We can specify the scheme, ready to build.
  - We are analyzing and quantifying the performance improvement in various environments
  - We are designing different variants of schemes
- Invention has been disclosed to USC Office of Technology and Licensing
  - File # 3096, 3230

Applications

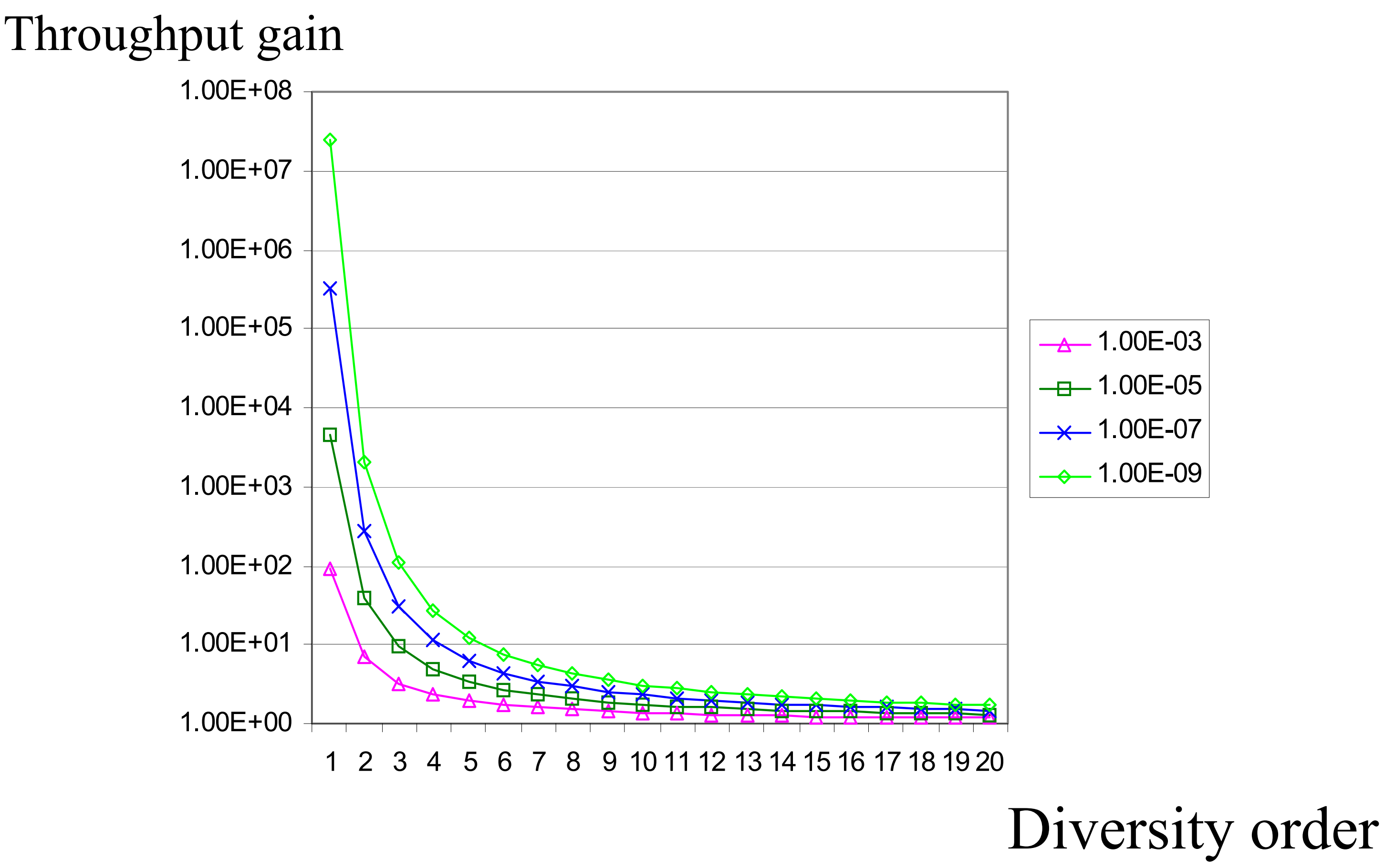
- Any mobile communication system that has to combat fading
- Special attention
  - Wireless multimedia: variable bit rate
  - Significant performance for fast moving users
    - Web surfing and multi-media in the train, high-way vehicles, etc.
- Market
  - Cellular service providers (CDMA)
  - Wireless data model to be considered.

Conclusions

- Fast rate adaptation can increase average data rate by thousand times.
- We have a method of doing extremely fast rate adaptation.

More details

Bit (symbol)-error constrained throughput gain



Topics

- Adaptation
- Feedback

Unique features

- Why can’t current system do it?
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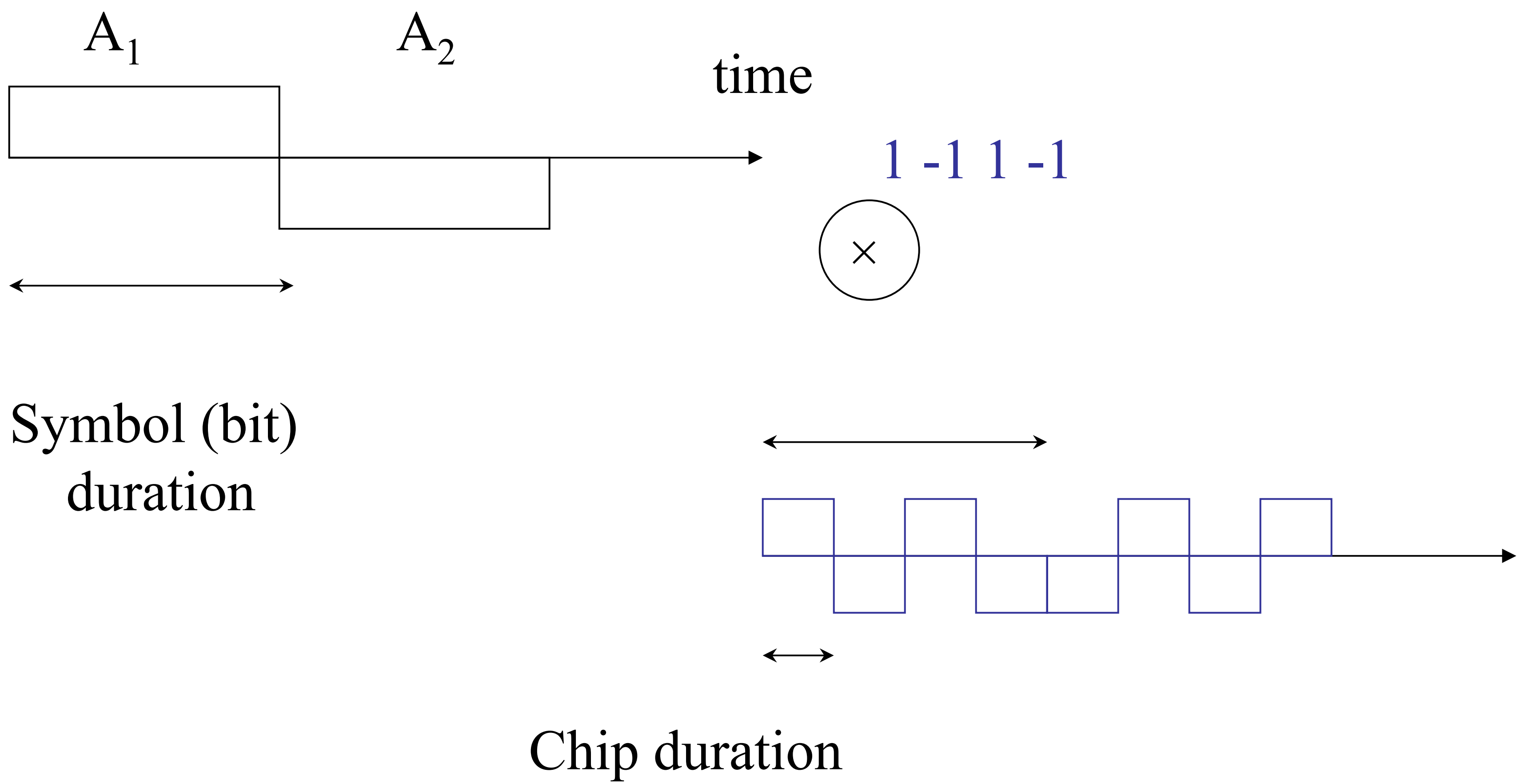
CDMA Networks



In this example, symbol duration = 4 * the chip duration.

How?

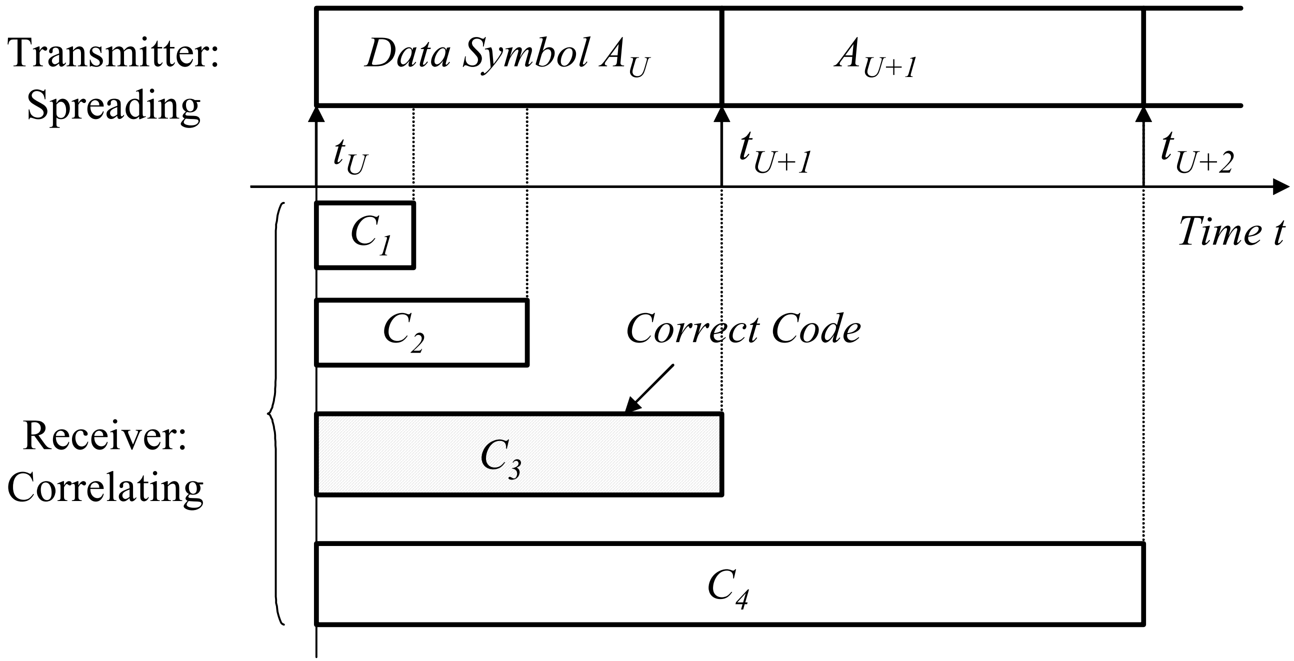
- Clever design and use of sequences modulating the transmitted signal :
  - A set of OVSF (orthogonal variable spreading) codes

$$C_1 = [++--]$$

$$C_2 = [++++----]$$

$$C_3 = [++++++++--------]$$

$$C_4 = [++++++++++++++++----------------]$$



For simplicity, we can impose a rule:

Sequnce C can only begin at time $n|C|$.

Applications

- Any mobile communication system that has to combat fading
- Special attention
  - Wireless multimedia: variable bit rate
  - Significant performance for fast moving users
    - Web surfing and multi-media in the train, high-way vehicles, etc.
- Market
  - Cellular system (CDMA)
  - Wireless ad hoc networks (?).

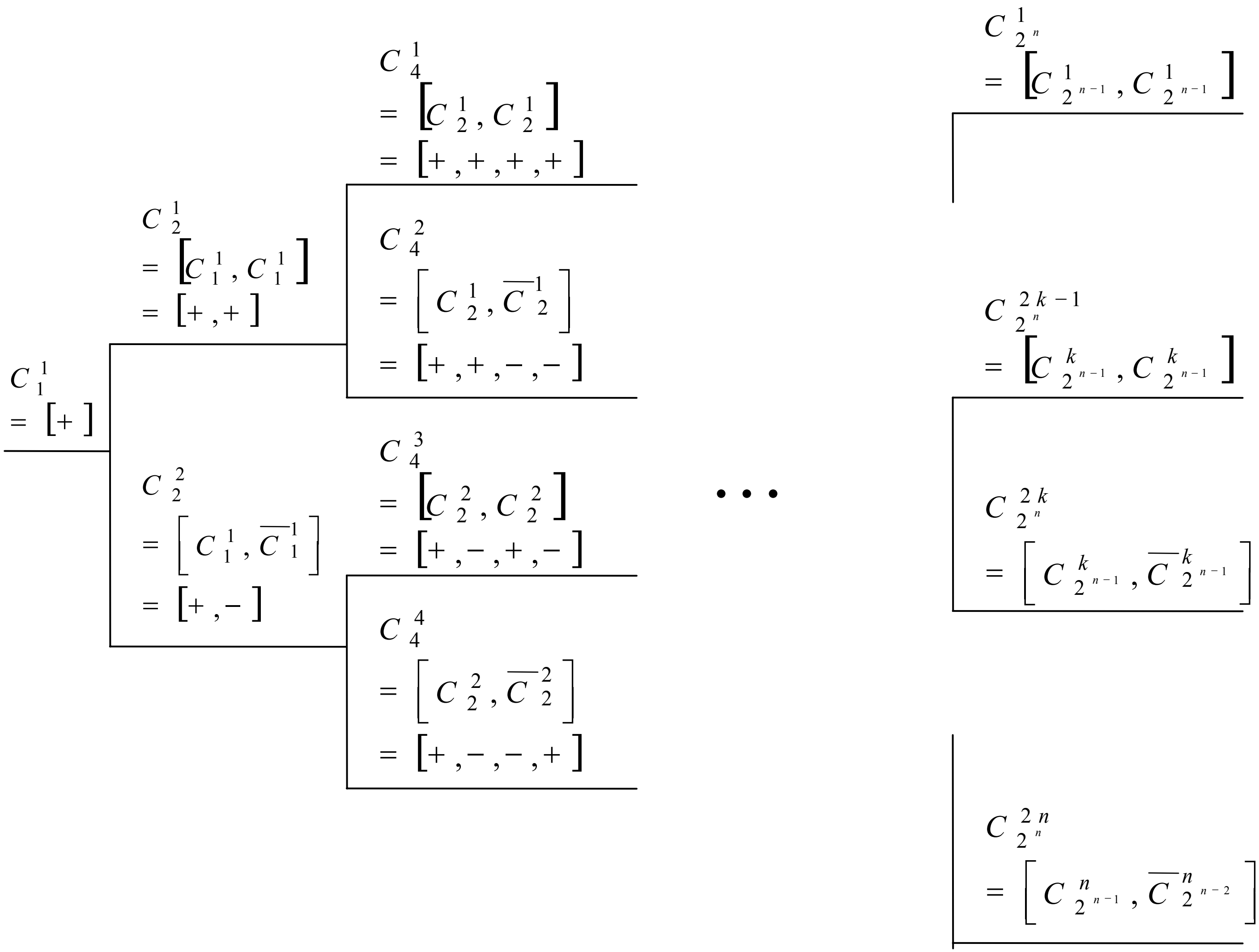
Issues: spectrum efficiency and code economy

- Bandwidth has been spread –> share bandwidth
- Ad hoc
  - Superimpose different PN codes to different users.
- Cellular-like point-to-multipoint system:
  - Some systems use OVSF codes as channelization codes; e.g., 3G .
  - There are a limited number of OVSF codes.
  - Must partition code space cleverly.

Code Allocation

- Well-known scheme: binary tree
  - Using Hadamard sequences
  - Not suitable for our symbol-by-symbol adaptation.
- We propose FOSSIL (Forest for OVSF-Sequence-Set-Inducing Lineages)

Well known OVSF codes generation



- Nodes with the depth = l from the root of the tree have codes of length = 2^l.

Note the properties

- Two codes are OVSF to each other as long as one is not a descendant of the other.
- Two codes are not OVSF if one is a descendant of the other.

Binary tree-structured OVSF codes generation

$$C^{1}_{1} = [+]$$

$$C^{1}_{2} = [C^{1}_{1}, C^{1}_{1}] = [+, +]$$

$$C^{2}_{2} = [C^{1}_{1}, \overline{C^{1}_{1}}] = [+, -]$$

$$C^{1}_{4} = [C^{1}_{2}, C^{1}_{2}] = [+, +, +, +]$$

$$C^{2}_{4} = [C^{1}_{2}, \overline{C^{1}_{2}}] = [+, +, -, -]$$

$$C^{3}_{4} = [C^{2}_{2}, C^{2}_{2}] = [+, -, +, -]$$

$$C^{4}_{4} = [C^{2}_{2}, \overline{C^{2}_{2}}] = [+, -, -, +]$$

$$\cdots$$

$$C^{1}_{2^{n}} = [C^{1}_{2^{n-1}}, C^{1}_{2^{n-1}}]$$

$$C^{2k-1}_{2^{n}} = [C^{k}_{2^{n-1}}, C^{k}_{2^{n-1}}]$$

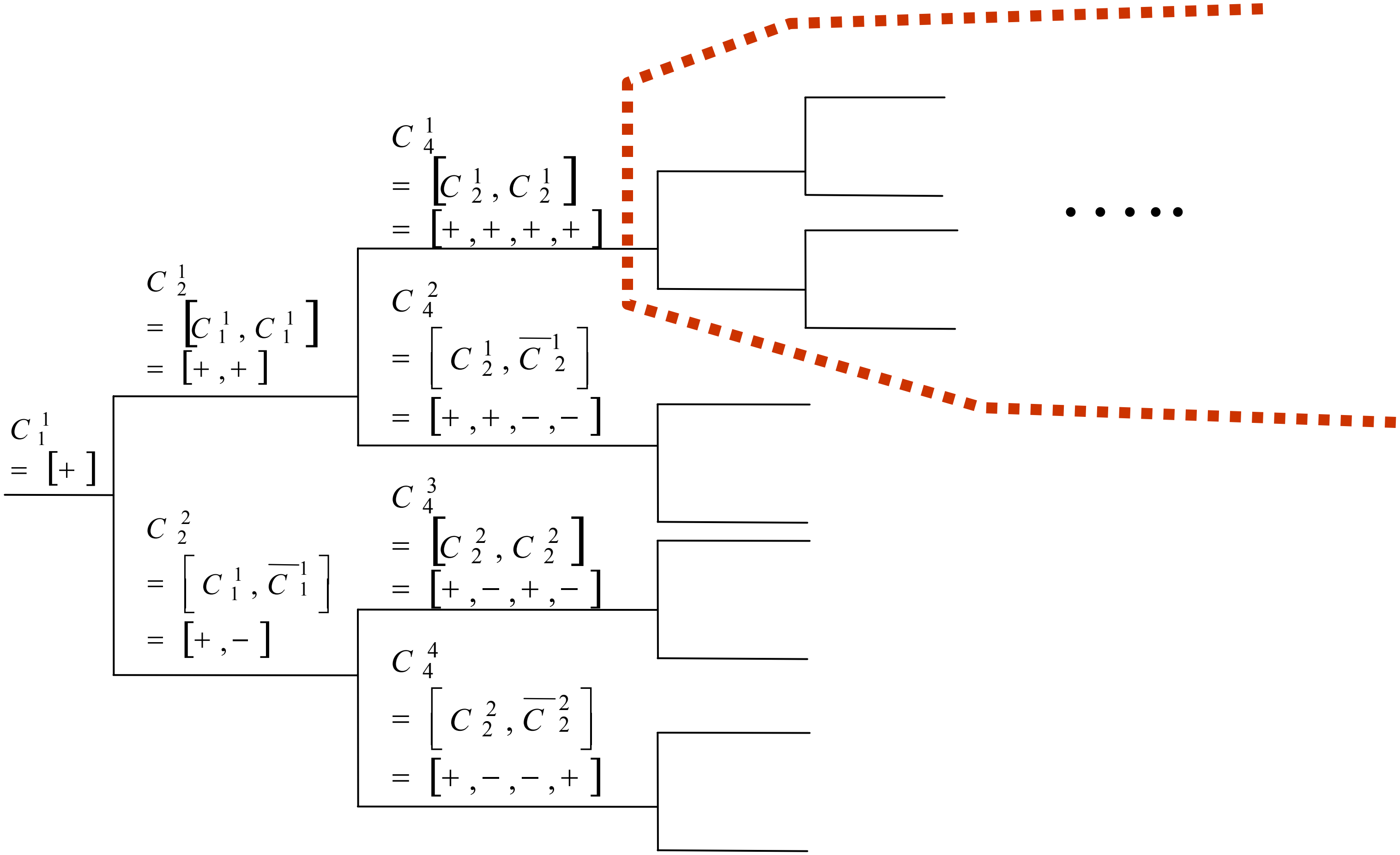
$$C^{2k}_{2^{n}} = [C^{k}_{2^{n-1}}, \overline{C^{k}_{2^{n-1}}}]$$

$$C^{2n}_{2^{n}} = [C^{n}_{2^{n-1}}, \overline{C^{n}_{2^{n-2}}}]$$

Some implications

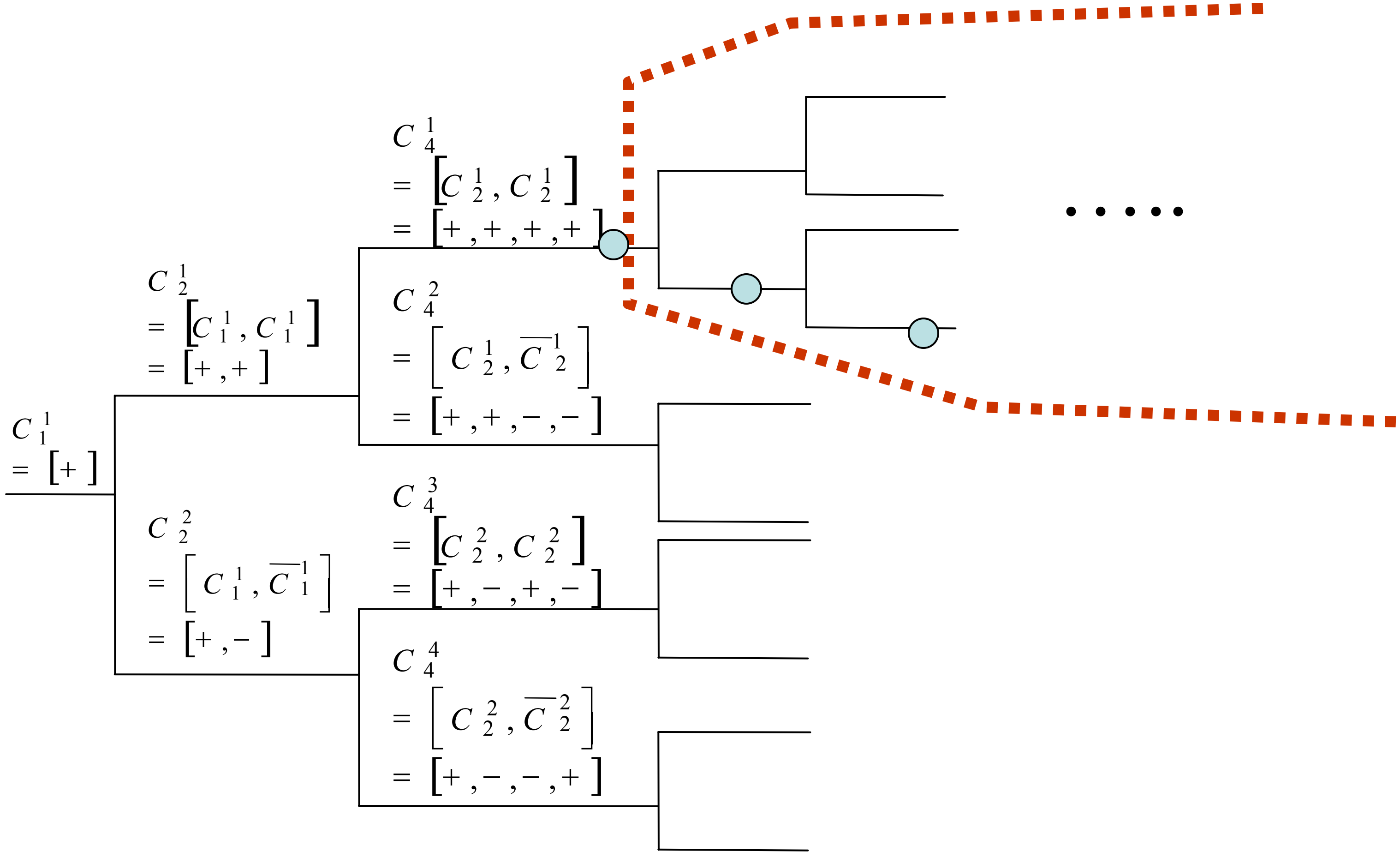
- An ancestor and descendant cannot be assigned to different users
- When assigning codes (sequences), one must pay attention to this constraint.
- For our scheme, codes with different lengths must be assigned to a user for rate adaptation.

Binary tree-structured OVSF codes generation



Important implications:

An ancestor and descendant cannot be assigned to different users

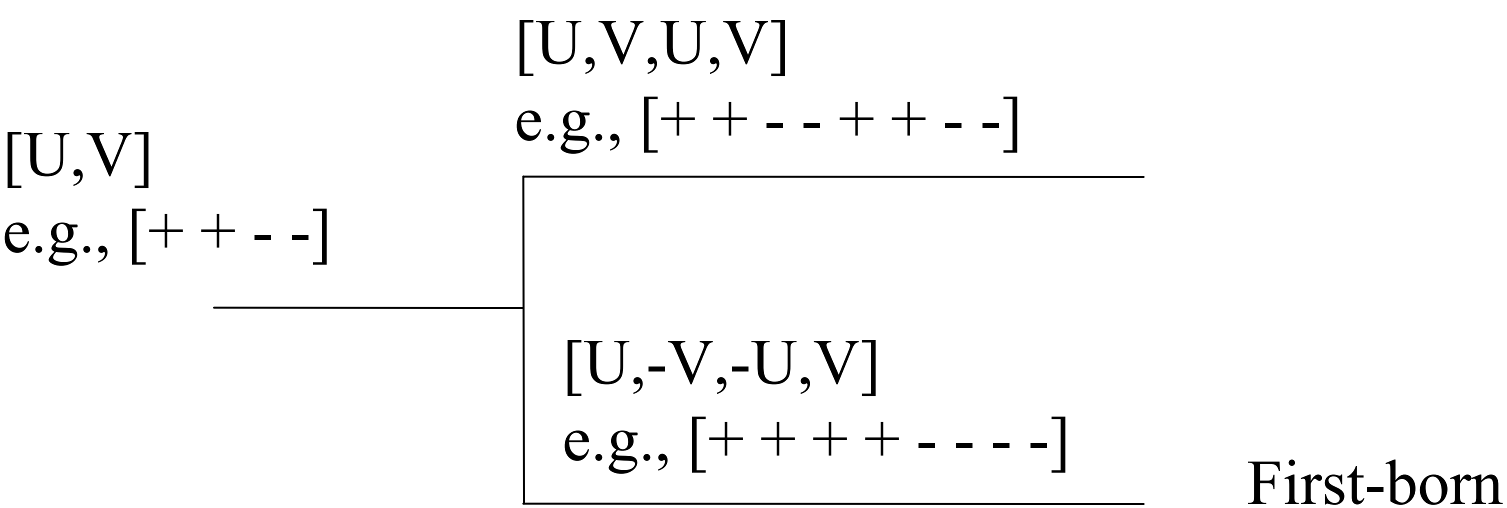


A branch is given to a single user, anyway.

Mult-rate is possible not not symbol-by-symbol.

We devised

- Forest-structured generation of OVSF codes
  - Multiple roots that are half-wise orthogonal.
- E.g. Roots [A,a], [B,b], [C,c], ..
  - First halves A,B,C,… are orthogonal.
  - Second halves a,b,c,.. are orthogonal.



- $C_{4}^{1} = [+,+,-,-]$
  - $C_{8}^{1} = [+,+,-,-,+,+,-,-]$
    - $C_{16}^{1} = [+,+,-,-,+,+,-,-,+,+,-,-,+,+,-,-]$
    - $C_{16}^{2} = [+,+,-,-,-,-,+,+,-,-,+,+,+,+,-,-]$
  - $C_{8}^{2} = [+,+,+,+,-,-,-,-]$
    - $C_{16}^{3} = [+,+,+,+,-,-,-,-,+,+,+,+,-,-,-,-]$
    - $C_{16}^{4} = [+,+,+,+,+,+,+,+,-,-,-,-,-,-,-,-]$
- $C_{4}^{2} = [+,-,+,-]$
  - $C_{8}^{3} = [+,-,+,-,+,-,+,-]$
    - $C_{16}^{5} = [+,-,+,-,+,-,+,-,+,-,+,-,+,-,+,-]$
    - $C_{16}^{6} = [+,-,+,-,-,+,-,+,-,+,-,+,+,-,+,-]$
  - $C_{8}^{4} = [+,-,-,+,-,+,+,-]$
    - $C_{16}^{7} = [+,-,-,+,-,+,+,-,+,-,-,+,-,+,+,-]$
    - $C_{16}^{8} = [+,-,-,+,+,-,-,+,-,+,+,-,-,+,+,-]$

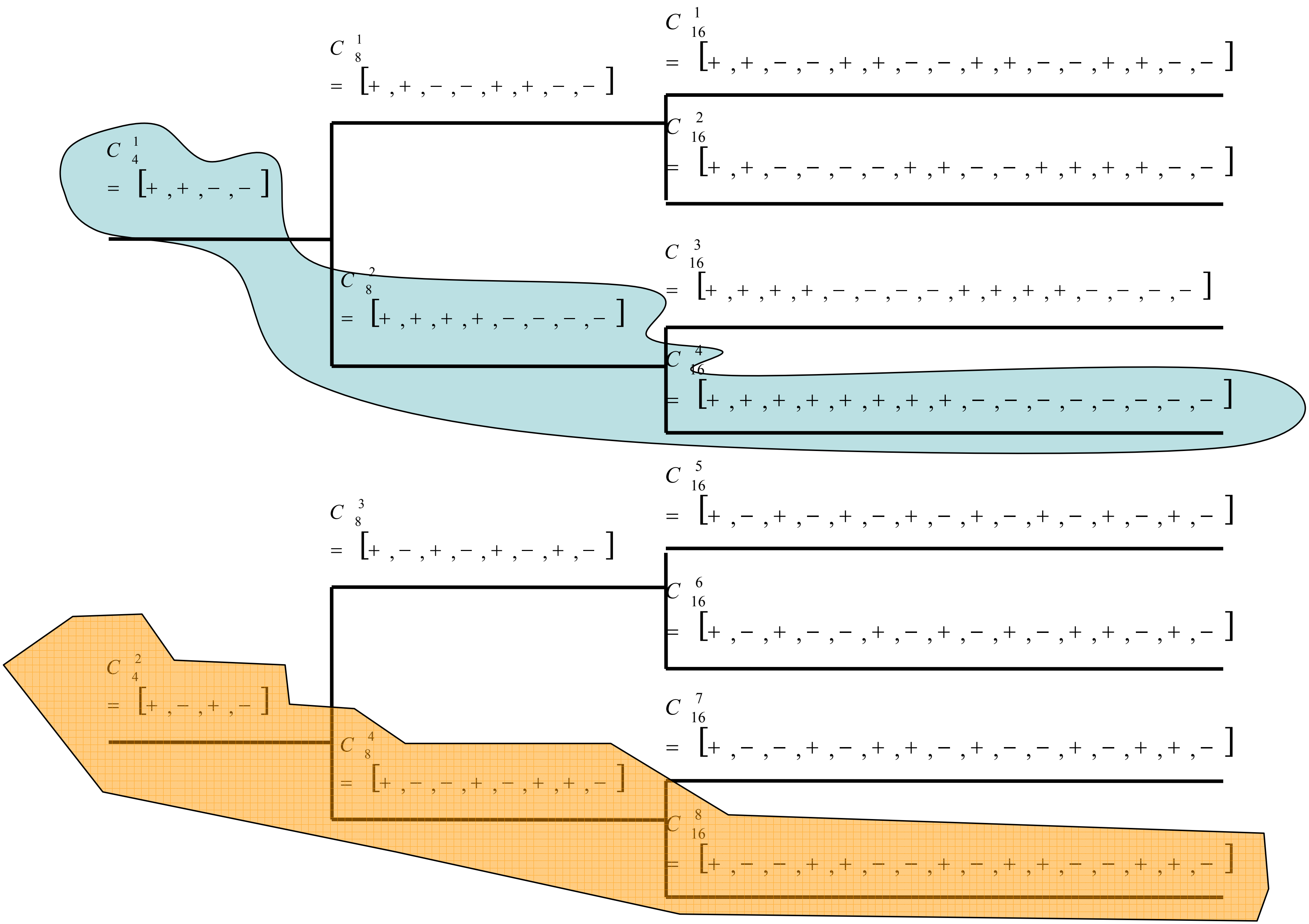
Important properties

- Two sequences are OVSF as long as one is not a descendant of the other. (Same as the tree-structured generation).
- Sequences in the first-born lineage are OVSF if one is a descendant of the other.

FOSSIL (Forest for OVSF-Sequence-Set-Inducing Lineages)

Implications

- An ancestor and descendant can be assigned to different users as long as the descendant is in the first-born lineage from the ancestor.



$C_4^1 = [+,+,-,-]$
$C_8^1 = [+,+,-,-,+,+,-,-]$
$C_8^2 = [+,+,+,+,-,-,-,-]$
$C_{16}^1 = [+,+,-,-,+,+,-,-,+,+,-,-,+,+,-,-]$
$C_{16}^2 = [+,+,-,-,-,-,+,+,-,-,+,+,+,+,-,-]$
$C_{16}^3 = [+,+,+,+,-,-,-,-,+,+,+,+,-,-,-,-]$
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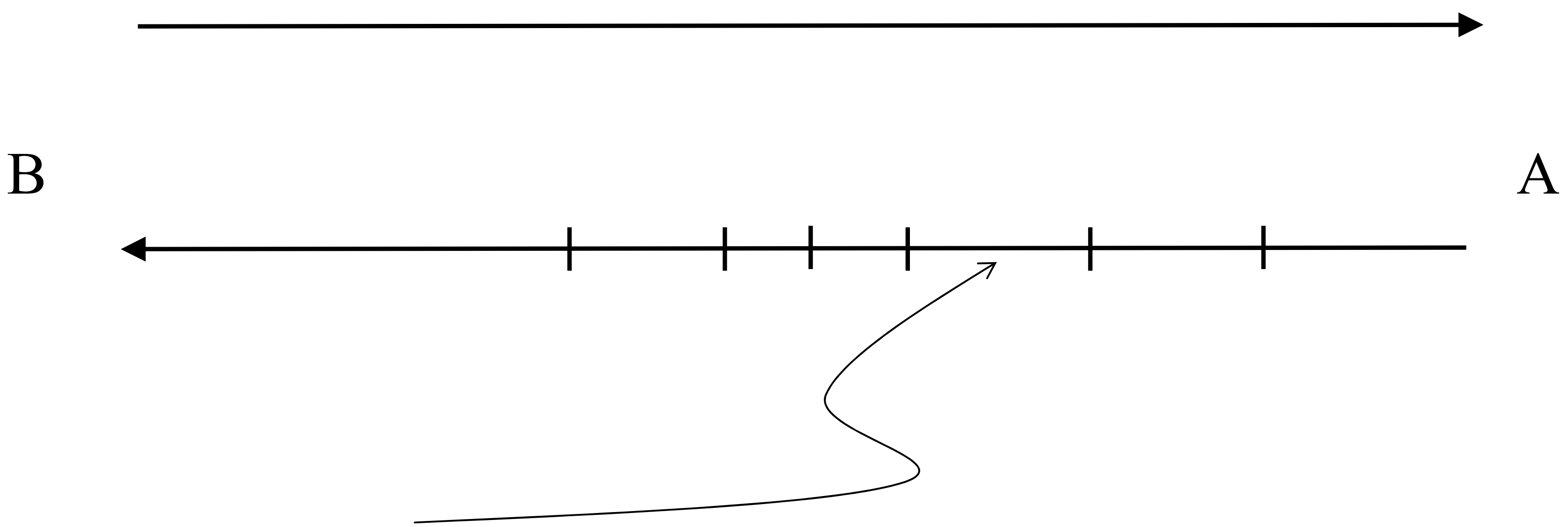
$C_{16}^8 = [+,-,-,+,+,-,-,+,-,+,+,-,-,+,+,-]$

Channel Feedback architecture and Protocols

Full-duplex link



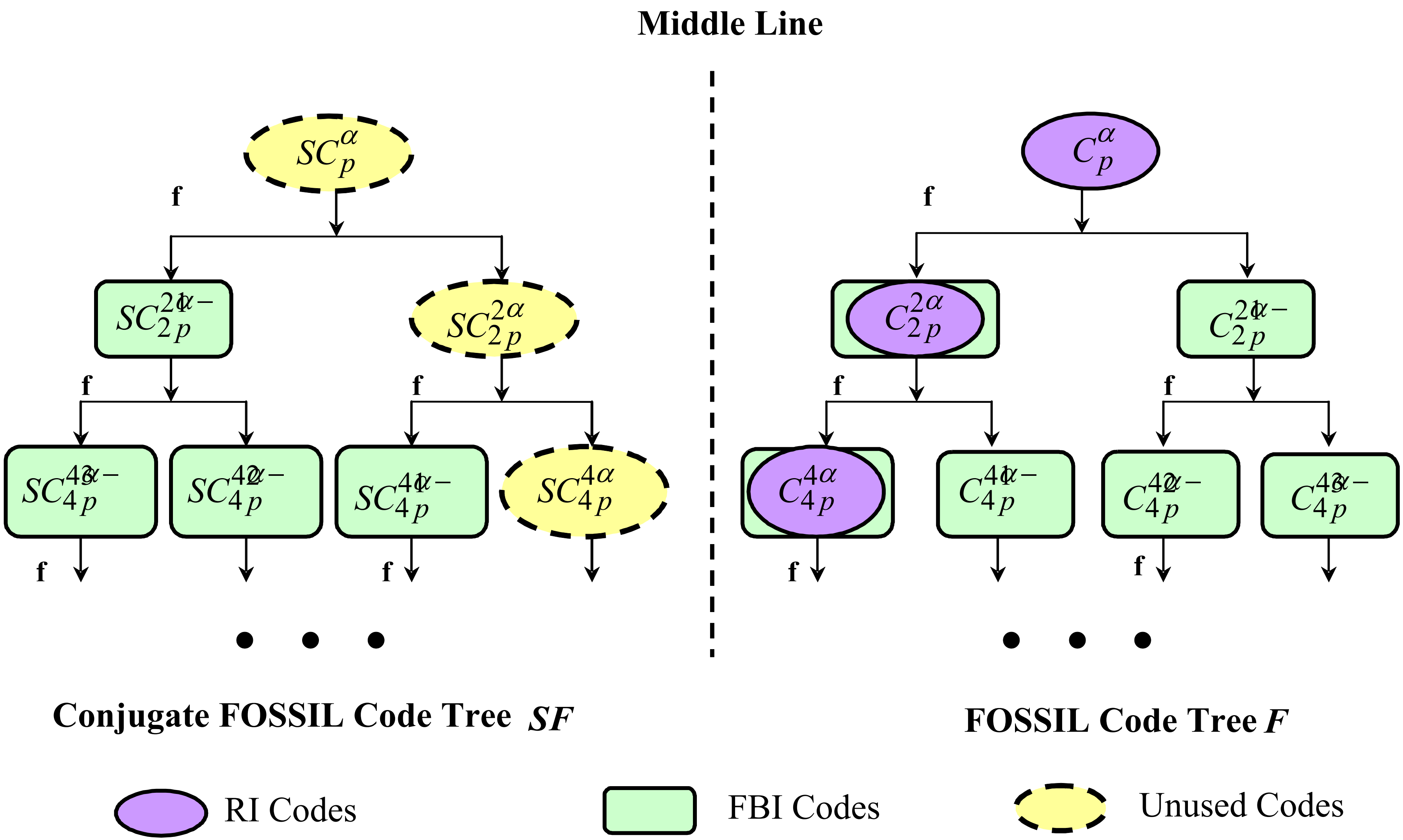
Choice of a spreading code indicates this symbol's duration and the status of channel BA

For Feedback Architecture with efficient code allocation

- Use FOSSIL and conjugate FOSSIL
- Conjugate FOSSIL
  - For FOSSIL Roots [A,a], [B,b], [C,c], .., consider another FOSSIL whose roots are [A,-a], [B,-b], [C,-c], ..

Conjugate Relation of Codes

- Code [X,Y] in FOSIIL's mirror image is [X,-Y] in conjugate FOSSIL


Middle Line
f
Conjugate FOSSIL Code Tree SF
FOSSIL Code Tree F
RI Codes
FBI Codes
Unused Codes

Protocol Overview

- For the same length, there are choices of codes.
- Designed some temporal rules that TX must obey in selecting a spreading for each symbol.
- Designed temporal rules in such a way that at each symbol allowable spreading codes are OVSF – receiver can detect by correlation.
- RX parses the symbol and also obtains the channel information from the the TX’s choice of the sequence and the temporal rule.

Conclusions

- Fast rate adaptation can increase average data rate orders of magnitude.
- We have a method of doing extremely fast rate adaptation.

Other Research and Engineering Experiences of Daniel Lee

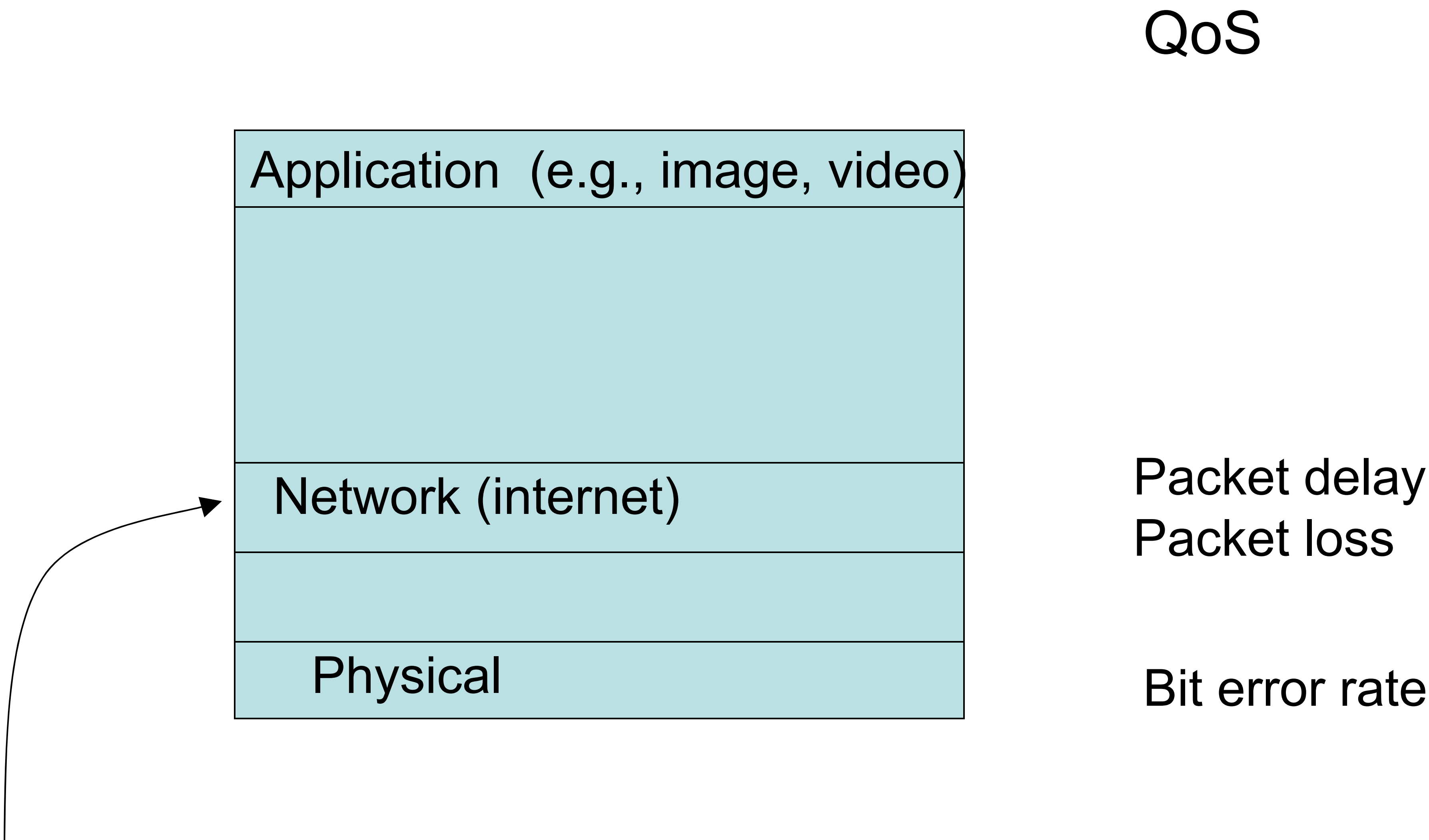
U.S. Naval Research Laboratory

- Unclassified Work:
  - Software Engineering of Network Signaling Protocols
  - Developing a network management system of ICEbox (U.S. government's information dissemination system)
    - SNMP (Simple Network Management Protocol)-based
  - Signal Processing of Reconnaissance data
    - Computational geometry

Daniel Lee's sampled research

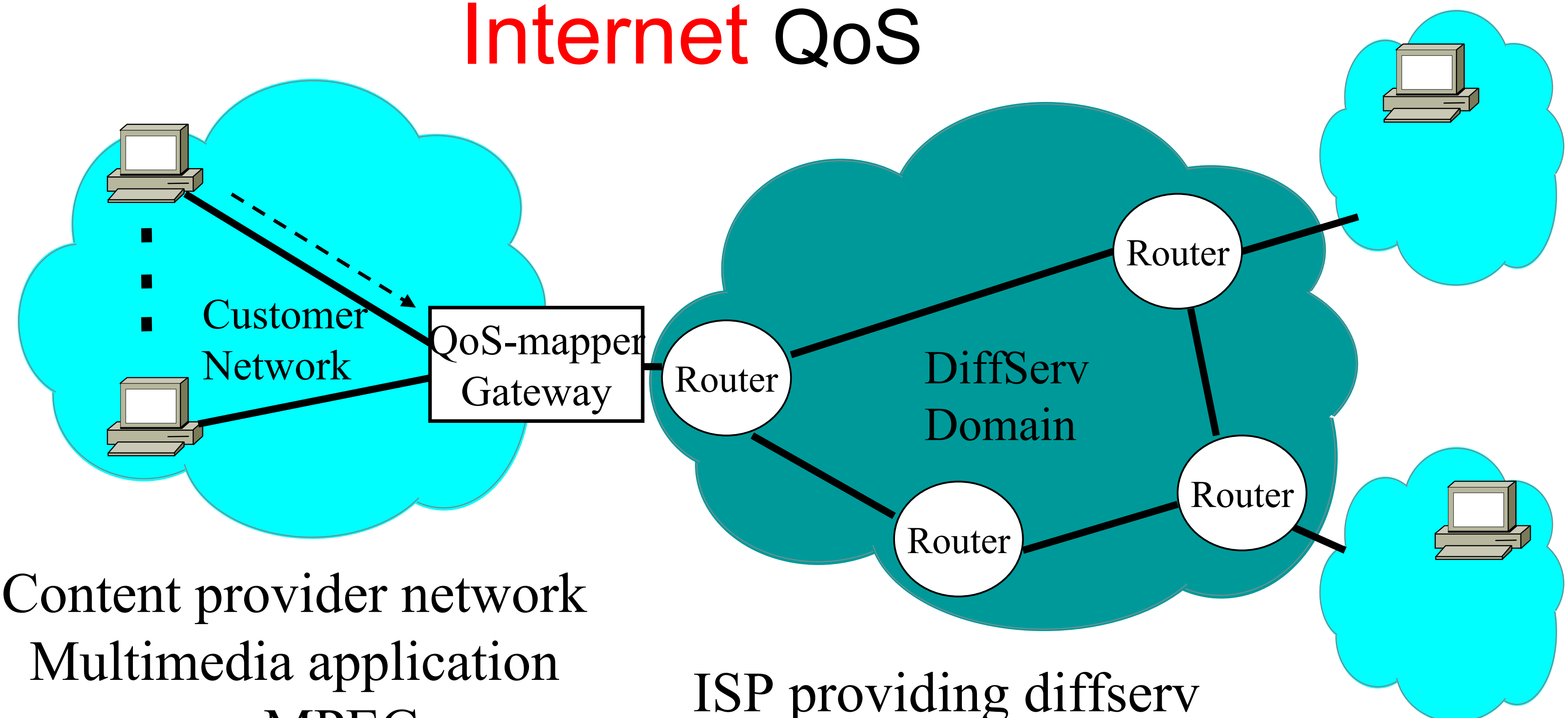
- Internet Quality of Service (QoS)
  - Internet Multimedia Transport
  - BE-aware QoS routing
  - Flow admission control (stochastic control)
- Call Admission Control of multi-service CDMA cellular networks
- Dynamic RWA problems of WDM networks
- Delay-tolerant networks, CCSDS File Delivery Protocols
- Sensor Networks, Ad hoc networks

Internet QoS: Network 101



The original internet never cared QoS.

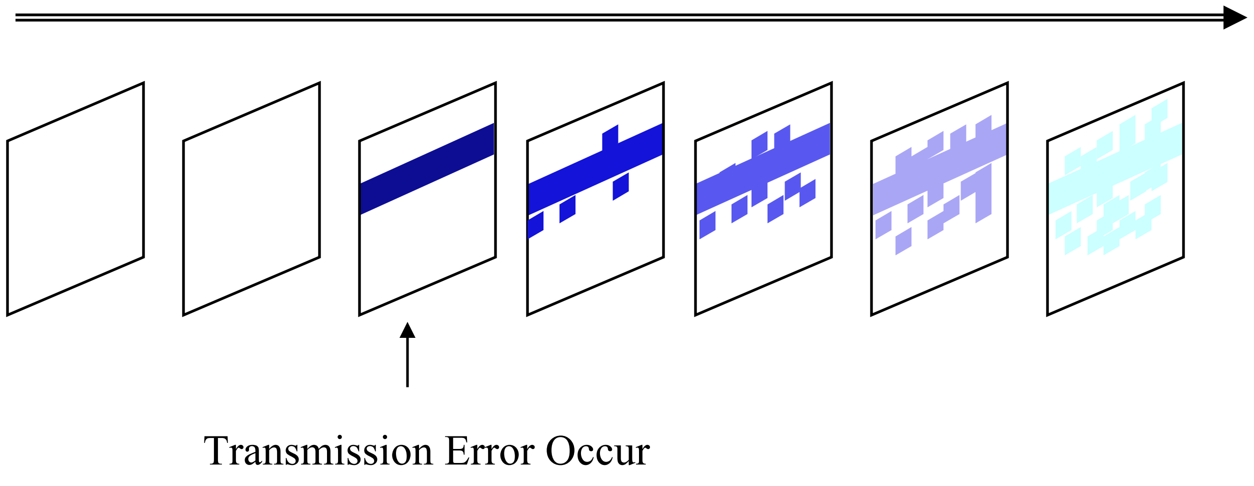
Internet QoS



Not all frames are created equal.

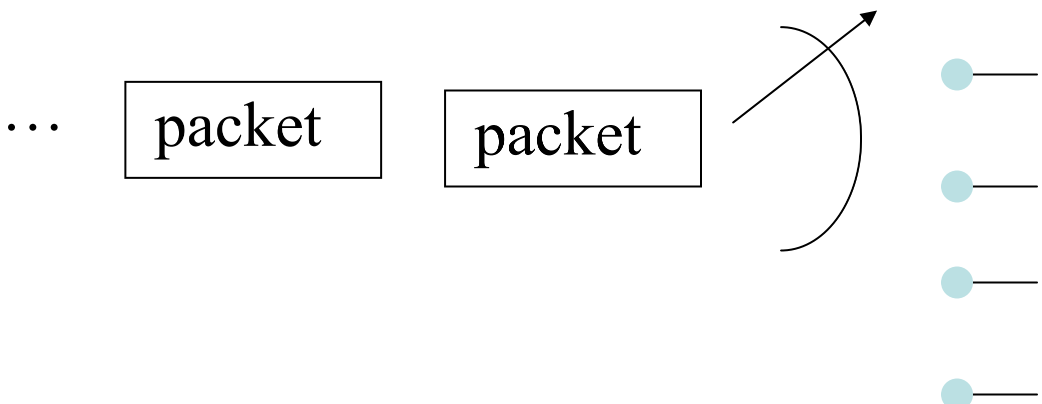
First	(σ_1,ρ_1)
Business	(σ_2,ρ_2)
Economy	(σ_3,ρ_3)
Best effort	(σ_4,ρ_4)

Application layer: e.g., MPEG, H.263 video, etc.



Mathematical Formulation

- Proper placement of packets into Diffserv classes



Class 1	(σ_1,ρ_1)
Class 2	(σ_2,ρ_2)
Class 3	(σ_3,ρ_3)
Class 4	(σ_4,ρ_4)

Best effort

under the constraint of SLA so that

- The end-user video qualities (PSNR) of different flows are optimized

Contributions

J. Shin, D. C. Lee, and C.-C. J. Kuo, *Quality of Service for Internet Multimedia,* Prentice Hall 2004.

Marriage between Signal Processing and Networks research.

Relating packet-level QoS (delay, loss) of a packet switching network to an application-level QoS.

Wish to apply to Telemedicine

- Telemedicine through IP
- Need to address Quality of Service
- Need to address Security and Privacy
  - Integrity and confidentiality
  - IP security

Call Admission Control in CDMA Cellular Networks

- Multi-class calls (e.g. data and voice), forward links
- Call arrivals and departures are random process.
- In CDMA, one call's signal is an interference to another's.
- There are also a limited number of channelization codes.
- Each class has a QoS requirement (SIR) and different traffic characteristics.

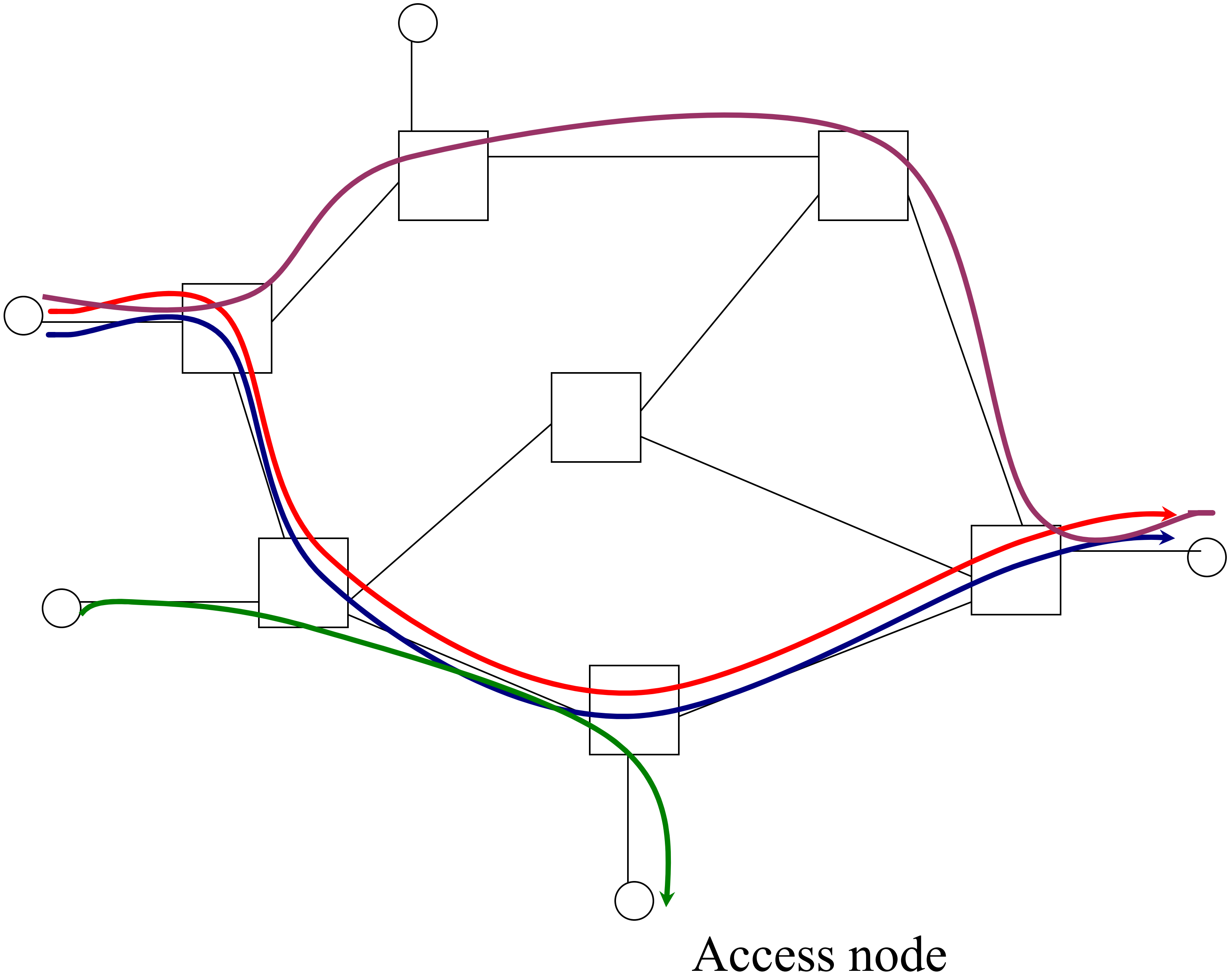
Highlights

- For each call arrival, the cell must decide whether to accept or reject. How to make that decision optimally?
- E.g. Maximize revenue

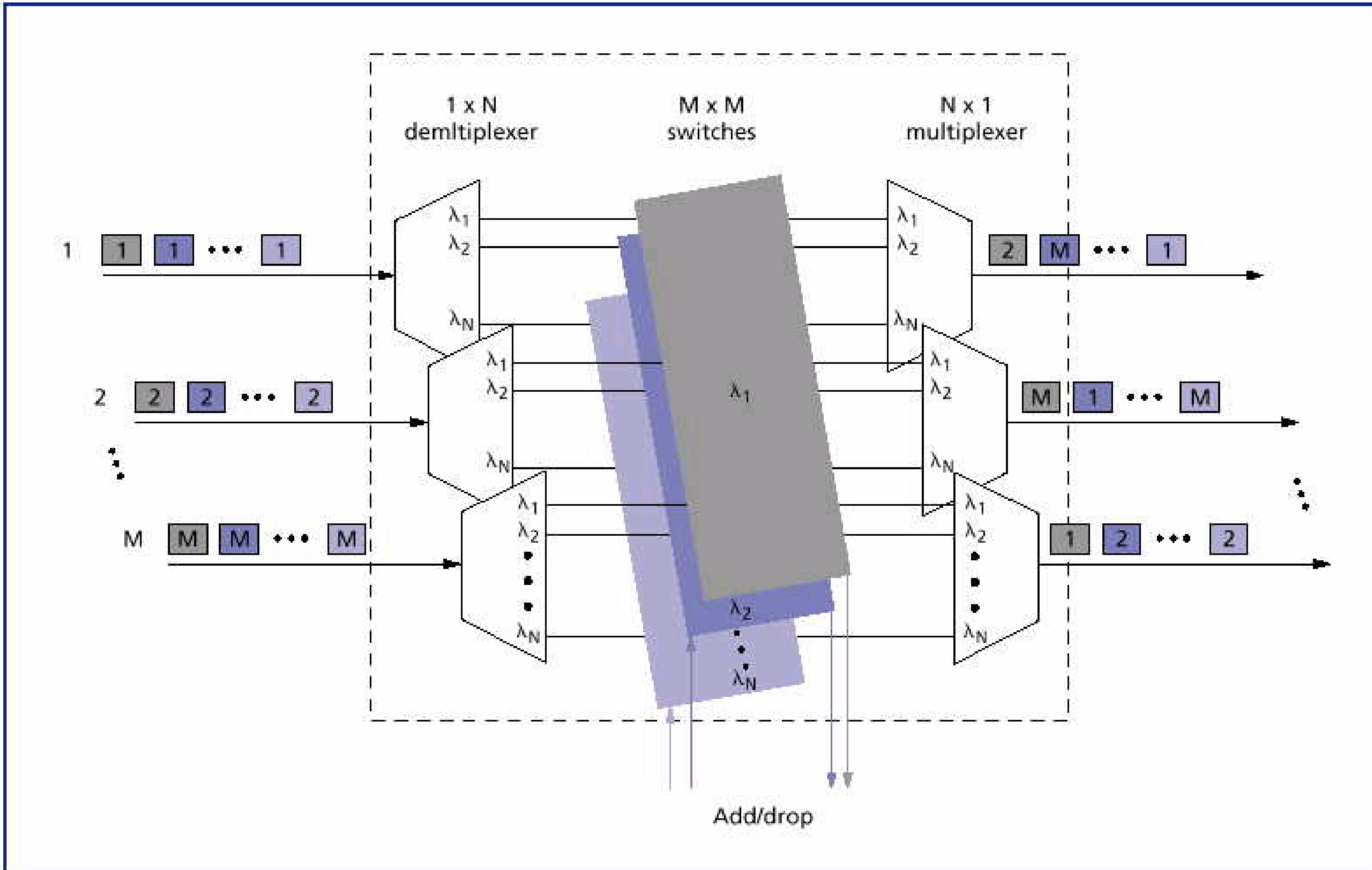
- Call-level QoS with considering packet-level traffic characteristics.
  - Methodology: physical –layer QoS
  - Methodology: Markov decision process

RWA of Optical Networks

- Dynamic Routing and Wavelength Assignment (RWA) of wavelength division multiplexing (WDM) networks
- No opto-electric conversion in switches.
- Calls arrive and depart randomly.


Access node

A typical Optical Crossconnect



All Optical Networks

- No opto-electrical conversion at a switch

Optical Networks Highlight

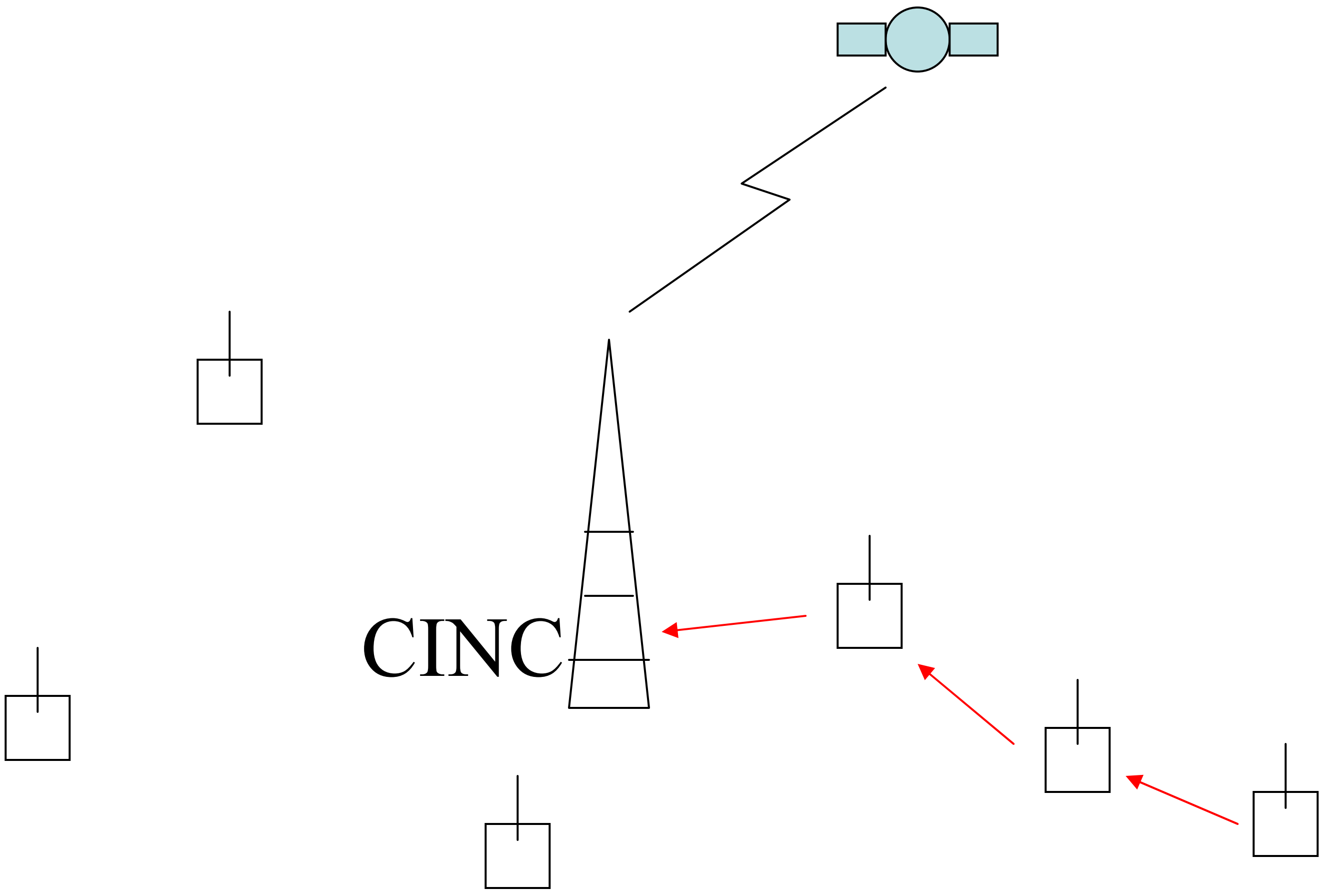
- Return of the circuit switching (?)
- Most problems are NP-hard or have state-space explosion.
  - Heuristics dominate the research
- Our contribution
  - So far, the best heuristics for future WDM network with multifiber cables with many fibers per cable and extremely many wavelengths per fiber

Wireless LAN

- 802.11 is mature.
- Ultra Wide Band Networks
  - DARPA, Telcordia, Boeing, EtherWire, USC

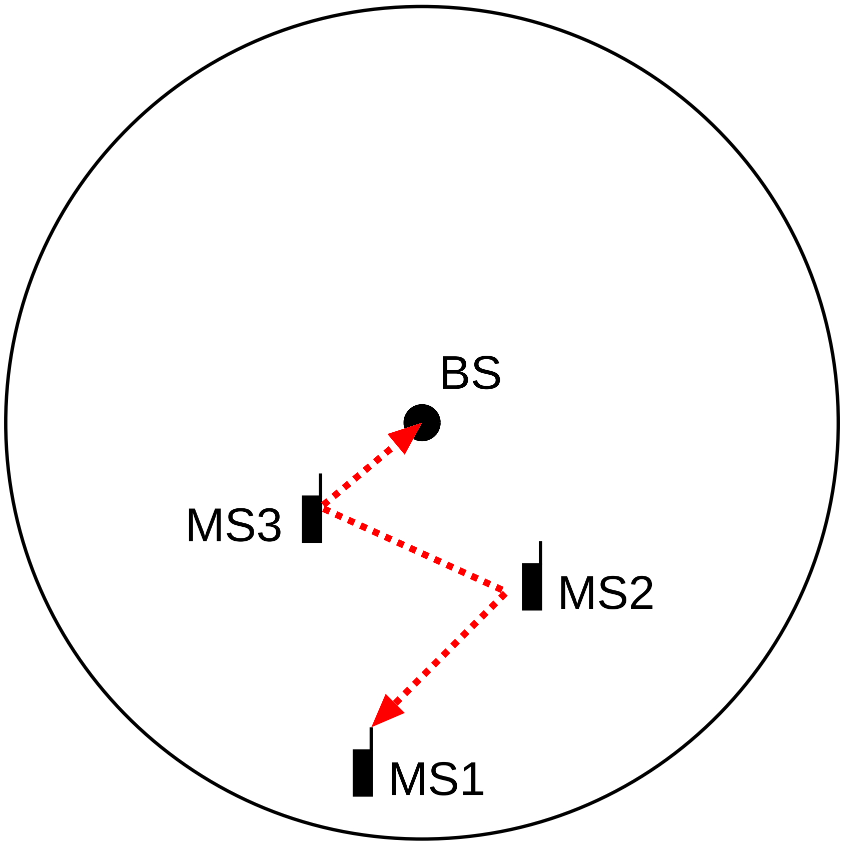
Routing in Ad hoc networks

- Commercial Value in wireless LAN?
- The Army is interested because Ad hoc network does not require any infrastructure.
- My argument:
  - The Army builds some infrastructure in the region



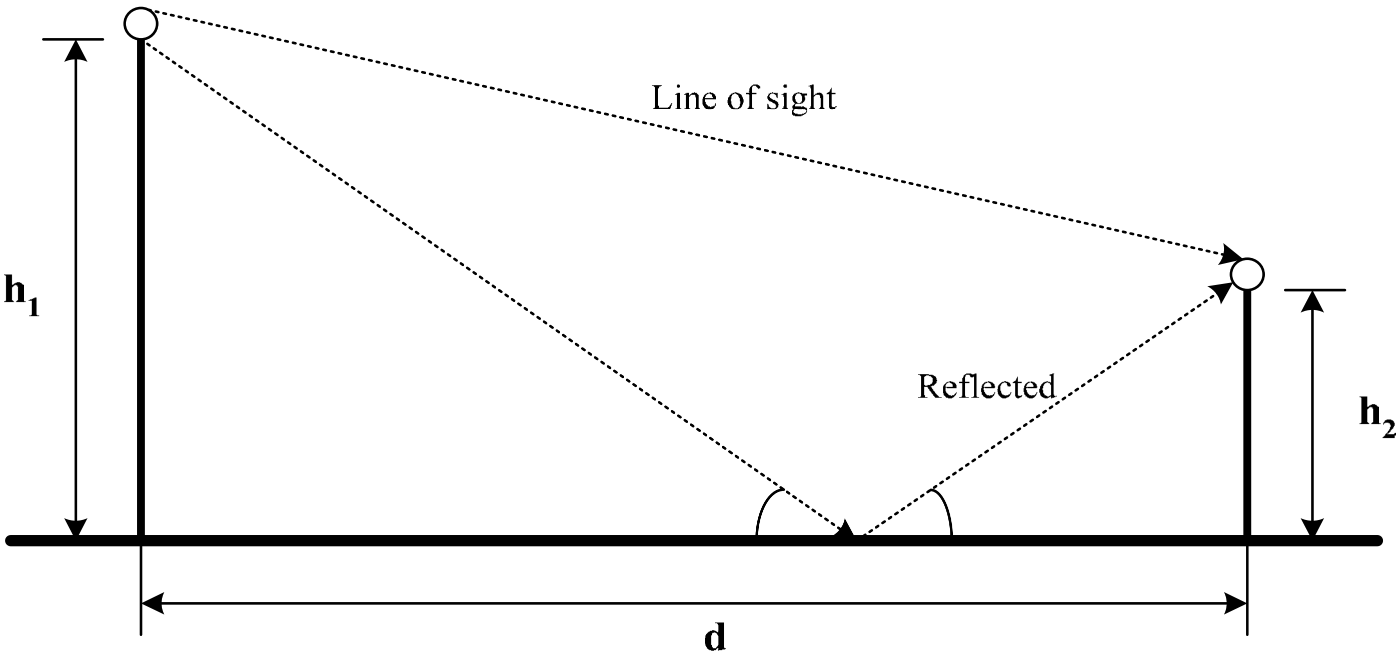
Cellular-like

Ad hoc packet relay protocols in a cellular-like environment



Lockheed Martin

Motivation: Propagation and path loss



$$d_1^4 + d_2^4 + \cdots + d_n^4 < \left(d_1 + d_2 + \cdots + d_n\right)^4$$

Less total TX power,
Less interference

Sensor Networks

- Tracking time-varying environmental parameters through sensor a network
- Distributed Estimation and Statistical Inference of
  - A large number of cheap sensors with poor calibration
  - Trading calibration with statistical inference from spatio-time correlation
  - Fundamental theoretical results
    - Similar to Kalman filtering, but not quite

Contents

- Current Telecommunications landscape
  - Daniel Lee's Research sampled
- ➔ Future Prospects: Vision of the long-term Telecommunication Research
  - Opportunities and Challenges
- How I would work as a professor and head of a subject

Vision for Long-Term Telecommunications Research

- Universal connectivity enabling diverse applications with proper
  - QoS
  - Reliability
  - Maintainability
  - Security
  - Evolvability
  - Reconfigurability
  - Mobility management
  - etc.

Research Opportunities

- Creating a connectivity
- Increasing the quality of service
- These are value-adding activities (commercial, humanitarian, scientific).
  - E.g., 802.11 and cellular
  - Airline passenger and a server, ….
  - Remote regions – underdeveloped area, scientific explorers
  - Space explorers
- Improve Securities, …ities
- New Systems
- New Applications
  - E.g., networked control

Challenges

- Heterogeneous media (QoS challenge)
  - Capacity difference between wireless and wired links
- Heterogeneous infrastructures
  - Cellular, WDM, internet, PSTN, WLAN, etc.
- Performance challenging environments
  - Intermittent links, networks with no contemporaneous paths
  - Long propagation delay of satellites and interplanetary links
- Diverse applications
  - Voice, data, video, interactive games, etc.

Long-term Research Framework: Universal Connectivity

- Wireless bottleneck
  - Wireless communication/networking research
    - OFDM, MIMO, etc.
    - Cross-layer joint design
    - Rapidly adaptive transmission
- Heterogeneity and performance-challenging environments
  - Delay-tolerant Networking