On MIMO and Multiuser Communication

Srikrishna Bhashyam

October 22, 2024

Department of Electrical Engineering, IIT Madras

Acknowledgements: Advisor, Students, Collaborators

About myself

- B.Tech. ECE, IIT Madras, 1996
- MS (1998) and PhD (2001)
  - Rice University, Houston, TX, USA
- Qualcomm 2001-2003

- Research interests
  - Communication and Information theory
    - Wireless communication
  - Statistical Signal Processing
    - Detection and Estimation
  - Resource allocation
    - Wireless networks

IITM coursework in those days

Course	Title	Cat	Cr	Gr	Att
First Semester (July-Nov 1992)					
CY101	Chemistry-I	S	4		
CY105	Chemistry Laboratory I	S	1		
HS131	History	H	3		
MA101	Mathematics I	M	3		
ME101	Engineering Drawing-I	A	3		
ME103	Workshop-I	A	2		
ME110	Thermodynamics	E	3		
NC101	NCC	N	0		
PH101	Physics I	S	3		
PH103	Physics Lab I	S	1		
Second Semester (Jan-May 1993)					
AM102	Engineering Mechanics-I	E	3		
CS110	Introduction To Computing	E	3		
CY110	Chemistry II	S	3		
HS120	English II	H	3		
MA102	Mathematics II	M	3		
ME102	Engineering Drawing II	A	3		
ME104	Workshop-II	A	2		
NC102	NCC	N	0		
PH102	Physics II	S	3		
PH104	Physics Lab II	S	1		
Third Semester (July-Nov 1993)					
AM201	Engineering Mechanics II	E	3		
EC201	Electric And Magnetic Circuits	E	4		
EC203	Introduction To Digital Systems	T	4		
EC205	Comp.Aided Drafting and Layout Design	A	3		
HS420	Economics	H	3		
MA103	Mathematics III	M	4		
PH201	Physics III	S	3		
Fourth Semester (Jan-May 1994)					
AM258	Fluid Mechanics	N	3		
EC204	Networks And Systems	T	4		
EC206	Principles Of Electronics	T	4		
EC208	Microprocessors and Microcomputers	T	4		
EC216	Digital Circuits Lab.	P	1		
EL214	Electro-Mechanical Energy Conversion	T	4		
MA104	Mathematics-IV	M	4		
ME203	Workshop-III	A	2		

Course	Title	Cat	Cr	Gr	Att
Fifth Semester (July-Nov 1994)					
EC301	Electronic Circuits	T	4		
EC303	Electromagnetic Fields	T	4		
EC309	Feedback Control Systems	T	4		
EC315	Analog Circuits Laboratory	P	1		
EC319	Microprocessor Lab	P	1		
EL307	Solid State Devices	T	4		
EL311	Principles of Communication Engg	T	4		
EL321	Elec.Machines & Control Engg.Lab.	P	1		
ME214	Heat Engines	N	3		
Sixth Semester (Jan-May 1995)					
EC322	Elec. & Electronic Measurements	T	4		
EC342	Analog Systems & Measurements Laboratory	P	1		
EE356	Analog Integrated Circuits	T	3		
EE625	Semiconductor Power Devices	T	3		
EL326	Analog Communication Systems	T	4		
EL332	Commn. Networks & Trans.Lines	T	4		
EL336	Adv.Electronics Lab.	P	1		
IL302	Industrial Lectures	N	1		
MT322	Material Science For Electronic Enggr.	N	3		
Seventh Semester (July-Nov 1995)					
EE362	Device Modelling	T	3		
EE403	Digital Communication Systems	T	3		
EE421	Introdn. To Digital Signal Proc.	T	3		
EE476	Introduction To Robotics	T	3		
EE614	Computer Communications & Network	T	3		
EL411	Advanced Communication Laboratory	P	1		
HS301	Literature And Life	H	3		
Eighth Semester (Jan-May 1996)					
EC498	Project	P	9		
EE623	Integrated Circuit Design	T	3		
EE733	Advanced Topics in Digital Signal Proc.	T	3		

Communications & Signal Proc.
Principles of Communication Engg.
Analog Communication Systems
Digital Communication Systems
Computer Communications & Networks
Intro to DSP
Advanced Topics in DSP

Analog and Digital Circuits
Electric and Magnetic Circuits
Introduction to Digital Systems
Microprocessors and Microcomputers
Networks and Systems
Principles of Electronics
Electronic Circuits
Analog Integrated Circuits
Integrated Circuit Design

Devices
Solid State Devices
Semiconductor Power Devices
Device Modelling

Coursework at Rice

Communications
Intro to Random Processes and Applications
Information and Coding Theory
Network Information Theory (Adv. Topics)

Signal Processing
Digital Signal Processing
Digital Image Processing
Source Coding and Compression
Advanced Digital Signal Processing
Detection Theory

Networks
Design and Control of Broadband Networks
Broadband Integrated Services Networks

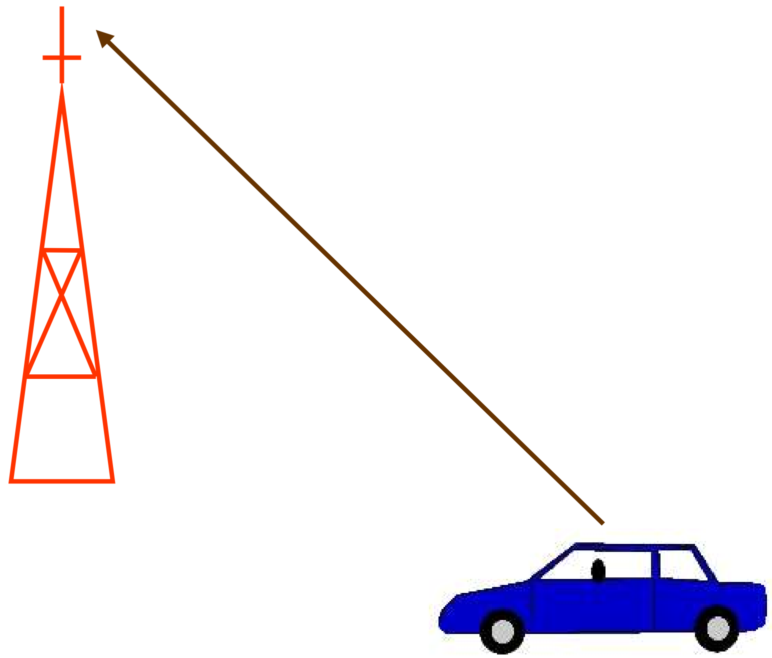
Control, Applied Mathematics
Numerical Linear Algebra
Approximation Theory

Research at Rice

- Had to choose problems to work on
- Excellent atmosphere
  - Regular seminars
  - Lot of excellent researchers
  - Great courses
  - Open environment
  - ECE, CS, Applied Math and Statistics in my building

Communication

- Information transfer from one point in space/time to another



Performance metrics and Resources

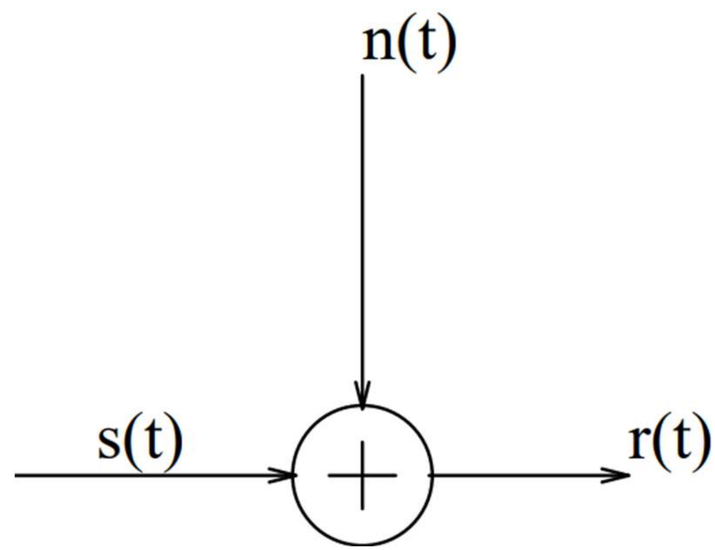
- Metrics
  - Reliable rate of information transmission
  - Delay

- Resources
  - Bandwidth
  - Transmit Power
  - Computational

Capacity

- Point-to-point bandlimited AWGN channel
- Delay, computational resources not constrained
- Transmit power constraint P
- Noise PSD N_0
- Bandwidth W

$$C = W \log\left(1 + \frac{P}{N_0 W}\right)$$

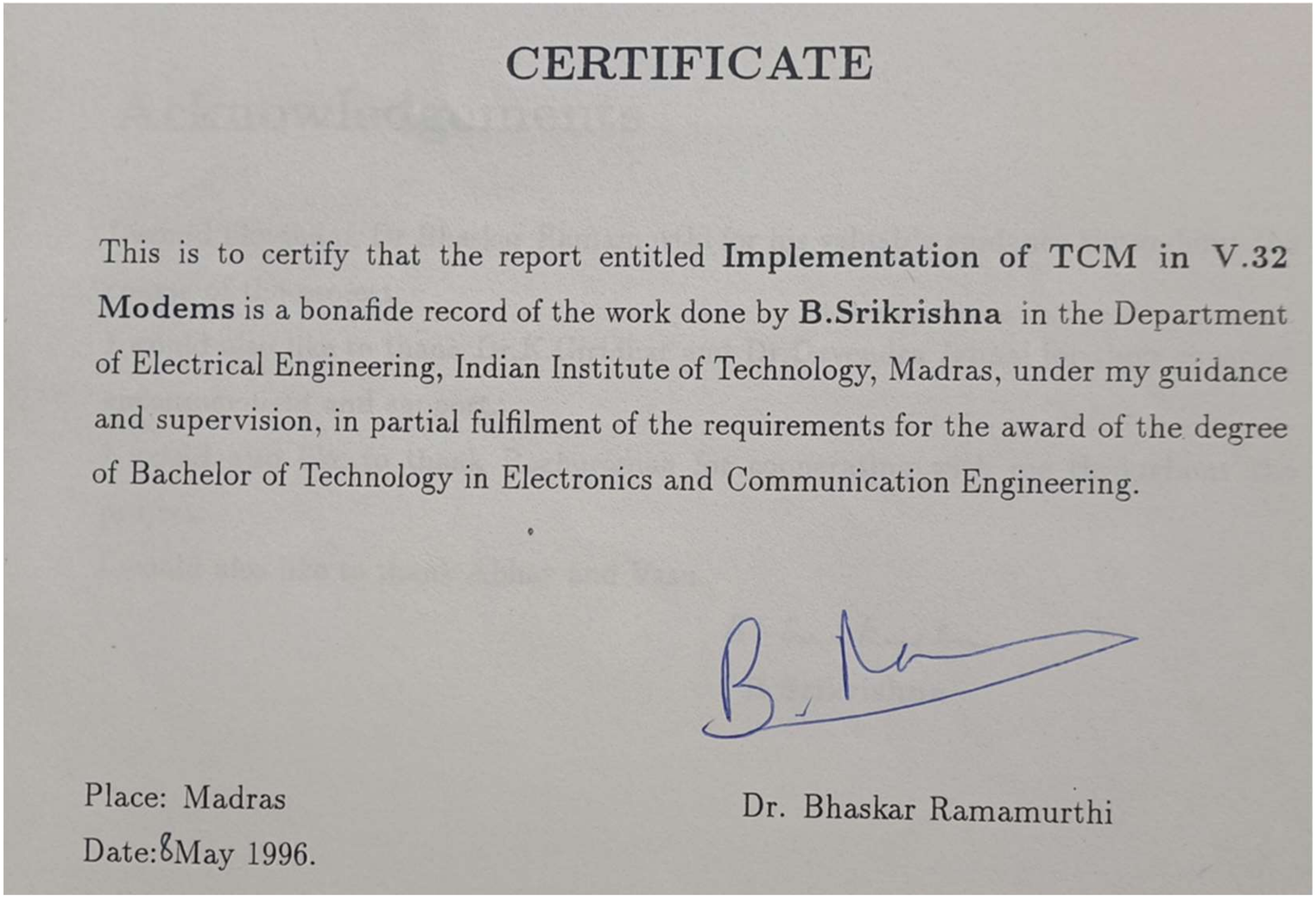


Capacity

- Point-to-point bandlimited AWGN channel with channel gain h

$$C(h) = W \ \log\left(1 + \frac{|h|^2 P}{N_0 W}\right)$$

First Communications Project



CERTIFICATE

This is to certify that the report entitled **Implementation of TCM in V.32 Modems** is a bonafide record of the work done by **B.Srikrishna** in the Department of Electrical Engineering, Indian Institute of Technology, Madras, under my guidance and supervision, in partial fulfilment of the requirements for the award of the degree of Bachelor of Technology in Electronics and Communication Engineering.

Place: Madras
Date: 8 May 1996.

Dr. Bhaskar Ramamurthi

With Profs. Bhaskar Ramamurthi and K. Giridhar

Wireline Modem Implementation

IMPLEMENTATION

- HALF-DUPLEX MODEM CAPABLE OF OPERATING AT 4800 bps & 9600 bps (16-QAM) AVAILABLE
- HALF-DUPLEX OPERATION AT 9600 bps, USING TCM AS THE MODULATION SCHEME IMPLEMENTED
- REQUIRED MODULES
  - DIFFERENTIAL ENCODER AND DECODER
  - CONVOLUTIONAL ENCODER
  - VITERBI DECODER
  - HARD DECISION DECODER

SIMULATION RESULTS

$E_{av,32\text{-}QAM}$: AVERAGE ENERGY OF THE CONSTELLATION

k : NO. OF BITS PER SYMBOL

σ^2 : VARIANCE OF NOISE

INPUT SNR per BIT

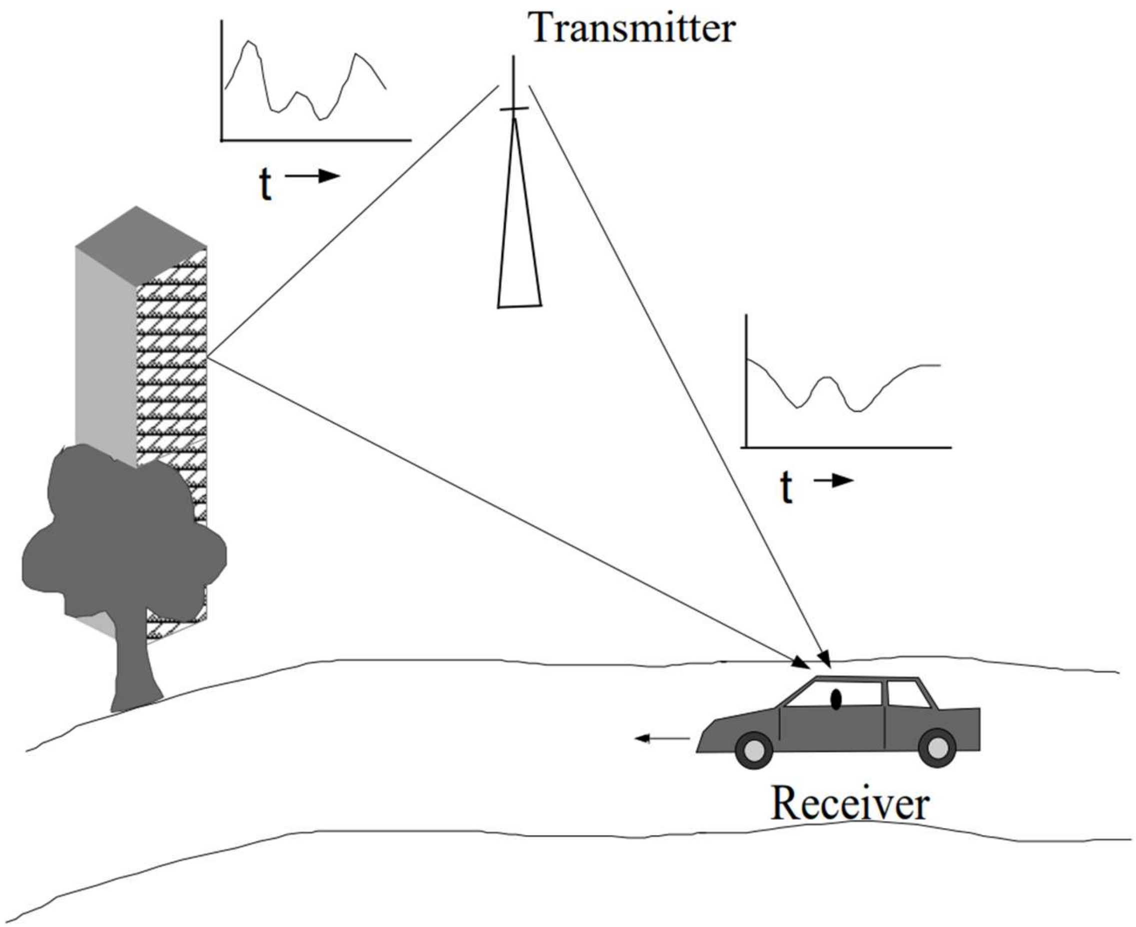
$$SNR = \frac{E_{av,32\text{-}QAM}}{2k\sigma^2}$$

SNR (dB)	SER 1	SER 2
6.02	1.05×10^{-1}	1.39×10^{-1}
6.62	2.9×10^{-2}	4.34×10^{-2}
7.26	8×10^{-3}	13.3×10^{-3}

SER1 : RESULTS FROM DSP ALGORITHM

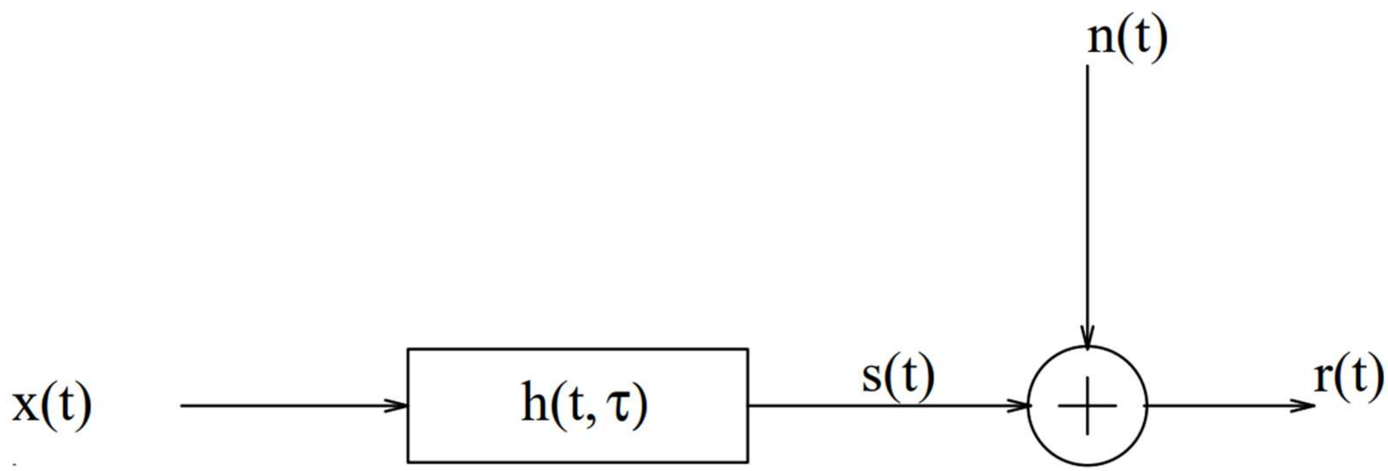
SER2 : RESULTS FROM C PROGRAM

Wireless Channel: Fading, Multipath, Doppler



Fading, Multipath, Doppler

- Channel models



Fading, Multipath, Doppler

- Defining the *spreading function* of the channel, $H(\theta, \tau)$,

$$H(\theta, \tau) = \int h(t, \tau) e^{-j2\pi\theta t} dt$$

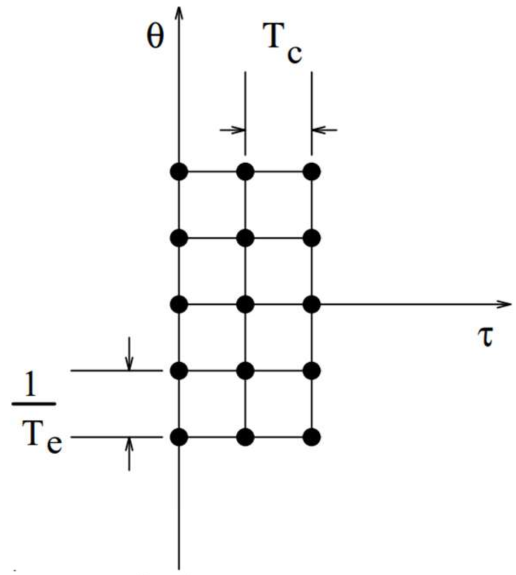
we can rewrite $s(t)$ as

$$s(t) = \int\int H(\theta, \tau) x(t - \tau) e^{j2\pi\theta t} d\theta d\tau$$

- Received signal - Linear combination of time and frequency shifted signals

P. Bello, "Characterization of Randomly Time-Variant Linear Channels," in IEEE Transactions on Communications Systems, vol. 11, no. 4, pp. 360-393, December 1963.

Fading, Multipath, Doppler

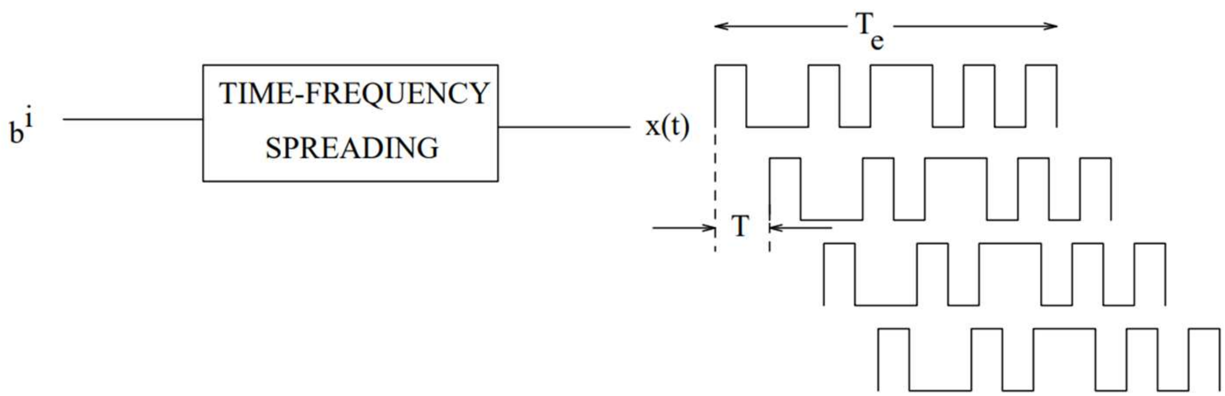


- Received signal - Sum of *finite number of time and frequency shifted versions* of the input signal with additive Gaussian noise [A. M. Sayeed, B. Aazhang, 1997]
- $N = \lceil \frac{T_m}{T_c} \rceil + 1, K = \lceil B_d T_e \rceil + 1$
  T_m = Multipath spread, B_d = Doppler spread

A. M. Sayeed and B. Aazhang, "Joint multipath-Doppler diversity in mobile wireless communications," in IEEE Transactions on Communications, vol. 47, no. 1, pp. 123-132, Jan. 1999.

Fading, Multipath, Doppler

Time-Selective Signaling

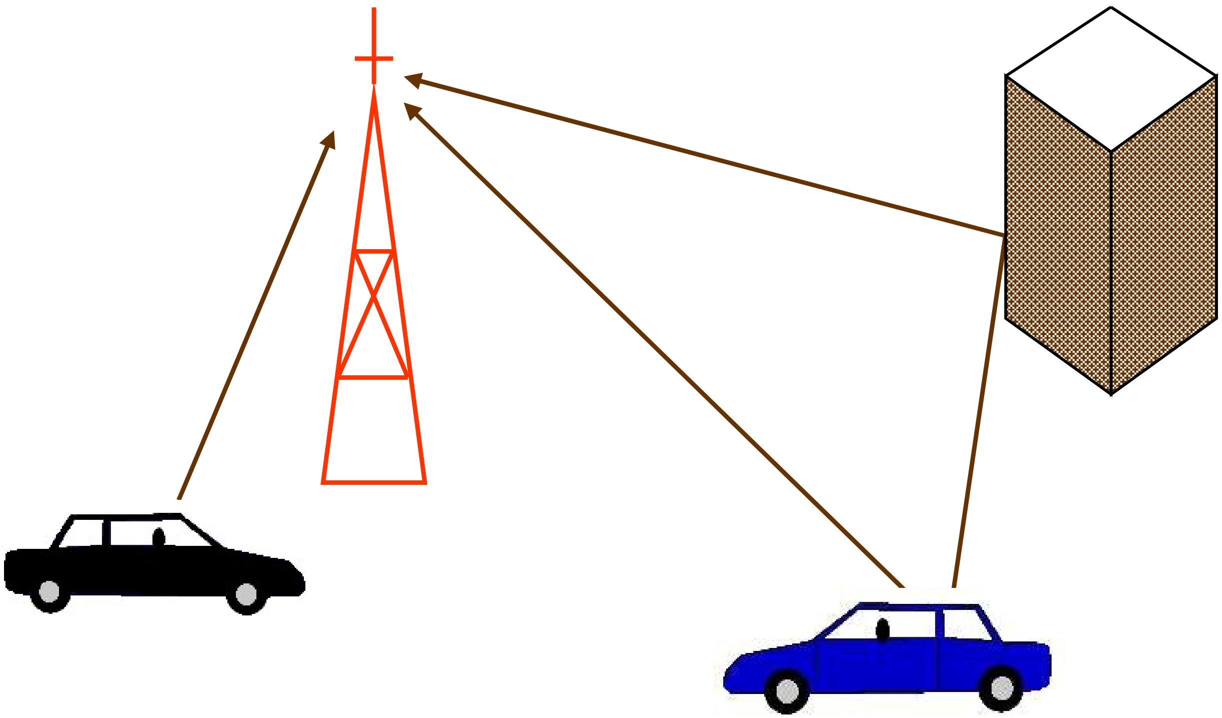


- *Increase symbol duration* for additional Doppler diversity
- Introduces inter-symbol interference (ISI)

S. Bhashyam, A. M. Sayeed , B. Aazhang , "Time-Selective Signaling and Reception for Communication over Multipath Fading Channels", IEEE Transactions on Communications, vol. 48, no. 1, pp. 83-94, Jan 2000.

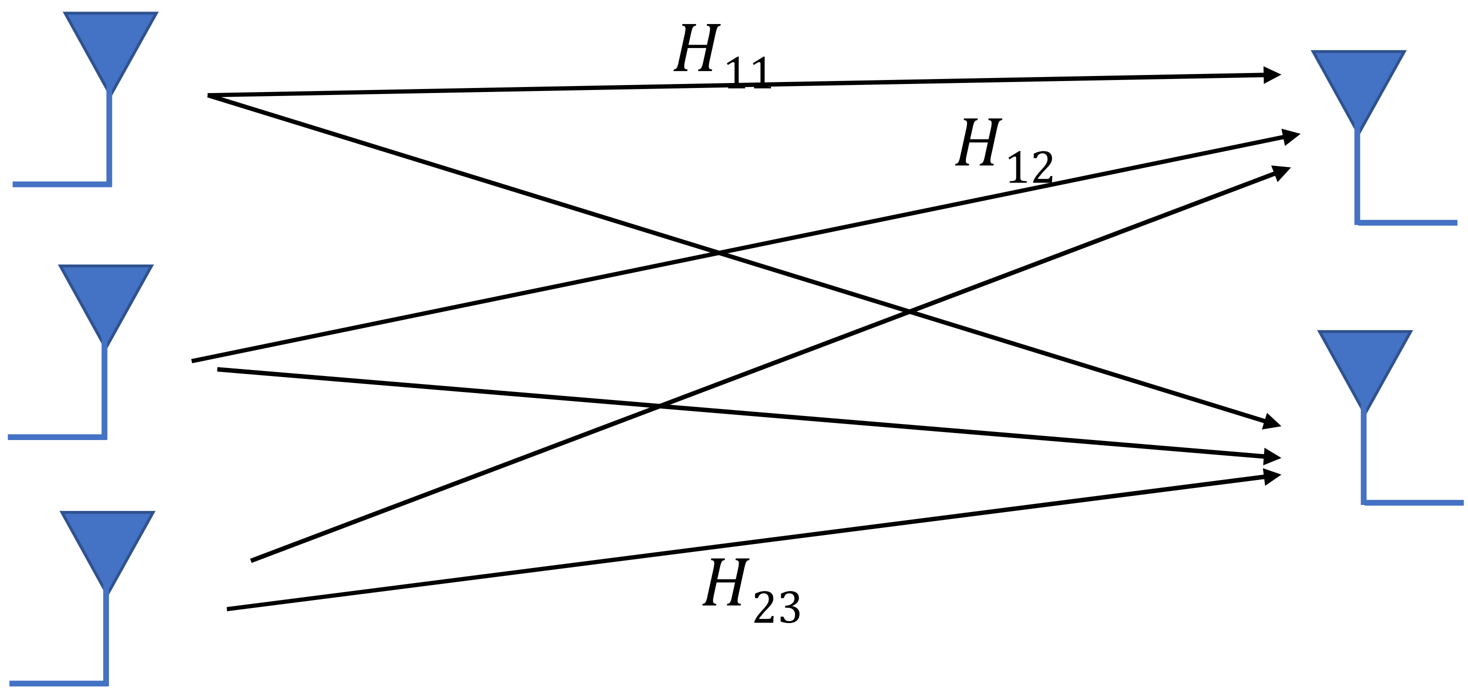
Cellular network

- Interference avoidance approach
- Network of point-to-point links



MIMO Communication

MIMO channel



$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$$

$\mathbf{x}$: N_t x 1 transmit vector

$\mathbf{H}$: N_r x N_t channel matrix

$\mathbf{y}$: N_r x 1 received vector

$\mathbf{w}$: N_r x 1 Gaussian noise

MIMO channel capacity: Fixed channel known at Tx and Rx

$$\text{Capacity } C(\mathbf{H}) = \max_{\mathbf{Q}} \log\left|\mathbf{I} + \mathbf{H}\mathbf{Q}\mathbf{H}^{\mathrm{H}}\right|$$

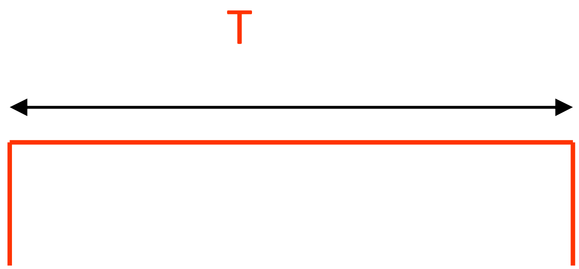
$$\text{subject to } \operatorname{trace}\{\mathbf{Q}\} \leq P$$

Singular Value Decomposition of $\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathrm{H}}$

Waterfilling power allocation

E. Telatar, "Capacity of multi-antenna gaussian channels," European Trans. on Telecomm., vol. 10, no. 6, pp. 585–595, 1999.

MIMO channel



- Fading channel
  - Slow or Fast relative to transmit duration
  - Channel known at the receiver
  - Outage probability and capacity (slow) $\mathrm{P}[C(\mathbf{H}) < \mathbf{R}]$
  - Ergodic capacity (fast) $\mathrm{E}[C(\mathbf{H})]$
  - Ergodic capacity increases linearly with $\min(N_t, N_r)$

E. Telatar, "Capacity of multi-antenna gaussian channels," European Trans. on Telecomm., vol. 10, no. 6, pp. 585–595, 1999.

V-BLAST

Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture

G.D. Golden, C.J. Foschini, R.A. Valenzuela and P.W. Wolniansky

The signal detection algorithm of the vertical BLAST (Bell Laboratories Layered Space-Time) wireless communications architecture is briefly described. Using this joint space-time approach, spectral efficiencies ranging from 20–40bit/s/Hz have been demonstrated in the laboratory under flat fading conditions at indoor fading rates. Early results are presented.

- 8 x 12 antennas system, 16-QAM from each tx antenna, 24.3 ksym/s, 30 kHz bandwidth

Golden, G.D., Foschini, C.J., Valenzuela, R.A. and Wolniansky, P.W., 1999. Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture. Electronics letters, 35(1), pp.14-16.

Space-Time Codes

- Codes for MIMO

744 IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. 44, NO. 2, MARCH 1998

Space–Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction

Vahid Tarokh, *Member, IEEE*, Nambi Seshadri, *Senior Member, IEEE*, and A. R. Calderbank, *Fellow, IEEE*

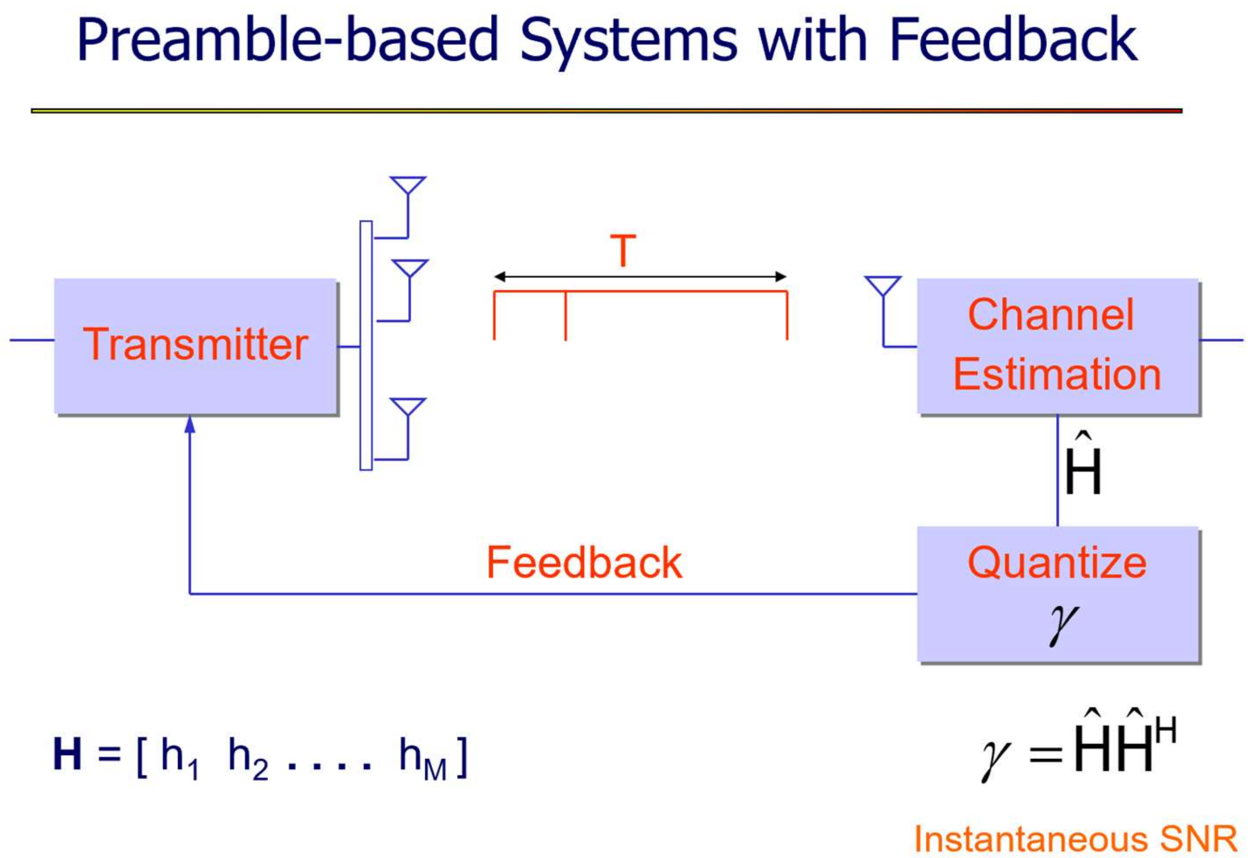
V. Tarokh, N. Seshadri and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," in IEEE Transactions on Information Theory, vol. 44, no. 2, pp. 744-765, March 1998

Diversity and Multiplexing

- Receive diversity
- Transmit diversity
- Spatial Multiplexing
- Diversity-Multiplexing trade-off

Lizhong Zheng and D. N. C. Tse, "Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels," in IEEE Transactions on Information Theory, vol. 49, no. 5, pp. 1073-1096, May 2003.

MISO with quantized channel feedback

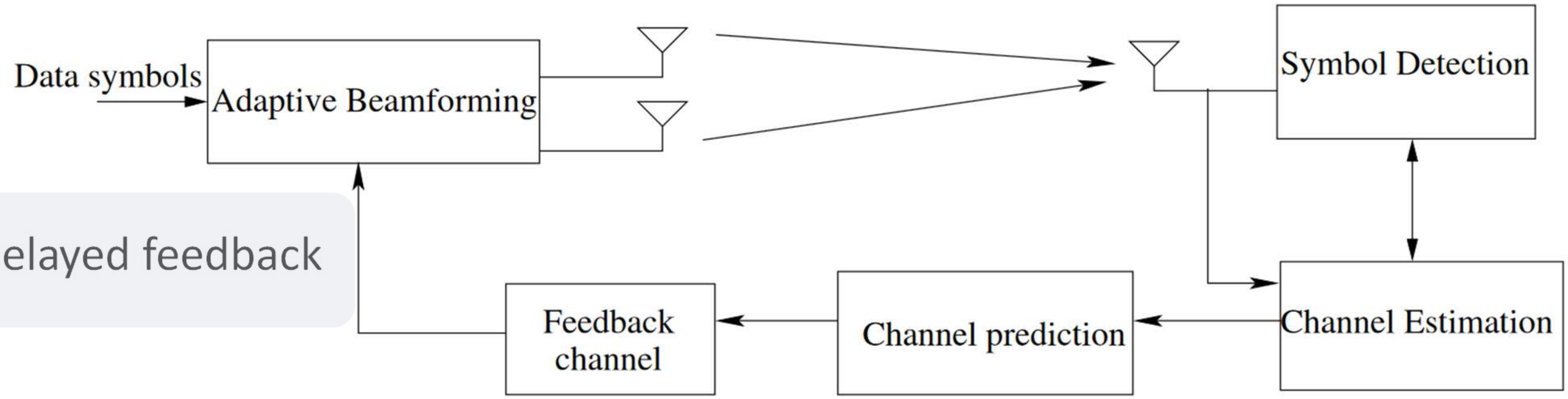


S. Bhashyam, A. Sabharwal, B. Aazhang , "Feedback Gain in Multiple Antenna Systems", IEEE Transactions on Communications, vol. 50, no. 5, pp. 785-798, May 2002.

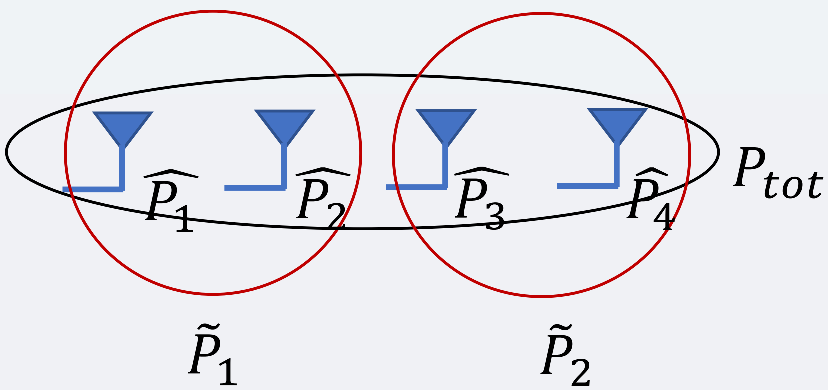
MIMO in Cellular Systems

- Introduced in 3G
  - Transmit/Receive diversity
  - Beamforming
  - 2 antennas
  - Used mainly in uplink receiver
- Spatial Multiplexing in 4G
  - 2 x 2 and 4 x 4
  - Single-user MIMO, Multi-user MIMO
  - Mainly Single-user MIMO
- 5G – Upto 64 data streams in downlink
- Multiuser MIMO in practice?
- Knowing the schemes that are implemented is not sufficient. Much deeper understanding is required.

Selected MIMO work at IITM



Delayed feedback



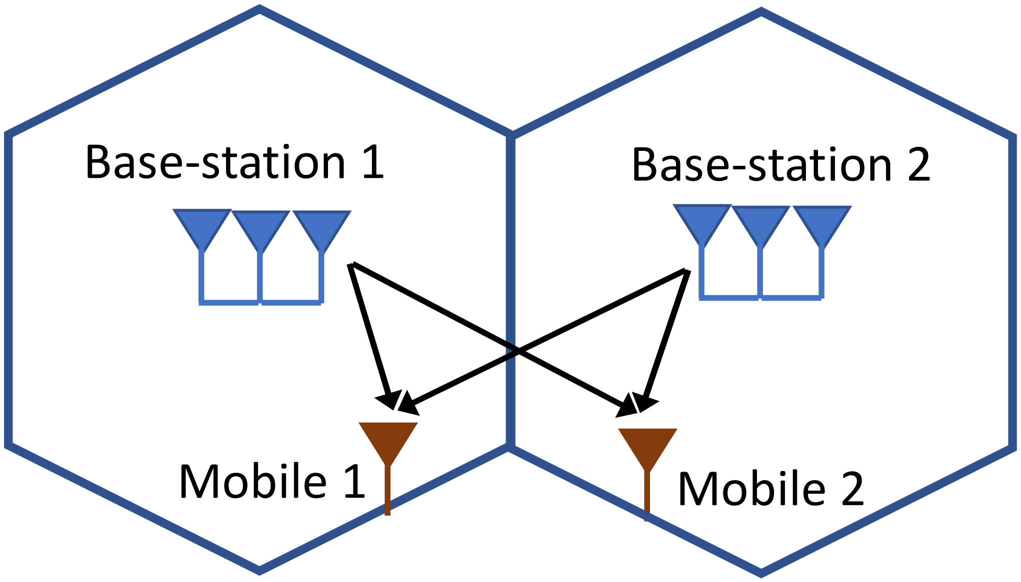
Multiple power constraints

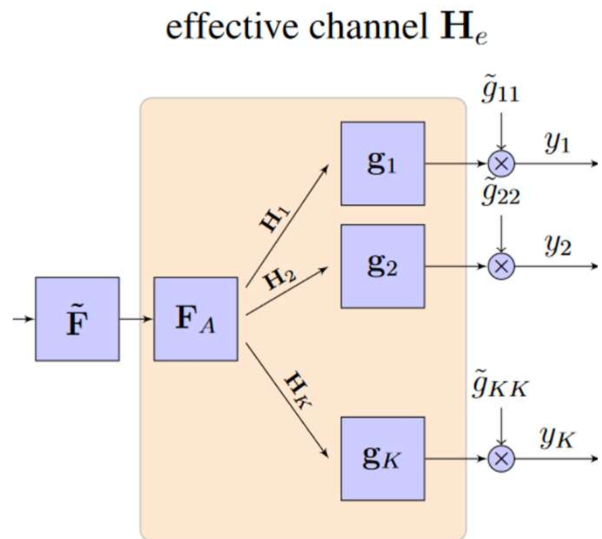
Distributed antennas

Hardware constraints

- V. S. Annapureddy, D. V. Marathe, T. R. Ramya, S. Bhashyam, "Outage Probability of Multiple-Input Single-Output (MISO) Systems with Delayed Feedback," IEEE Transactions on Communications, vol. 57, no. 2, pp. 319-326, Feb 2009.
- T. R. Ramya, S. Bhashyam, "Using delayed feedback for antenna selection in MIMO systems," IEEE Transactions on Wireless Communications, vol. 8, no. 12, pp. 6059-6067, December 2009.
- R. Chaluvadi, S. S. Nair, S. Bhashyam, "Optimal Multi-antenna Transmission with Multiple Power Constraints," IEEE Transactions on Wireless Communications, vol. 18, no. 7, pp. 3382-3394, July 2019.

Selected MIMO work at IITM





Distributed beamforming
Limited coordination

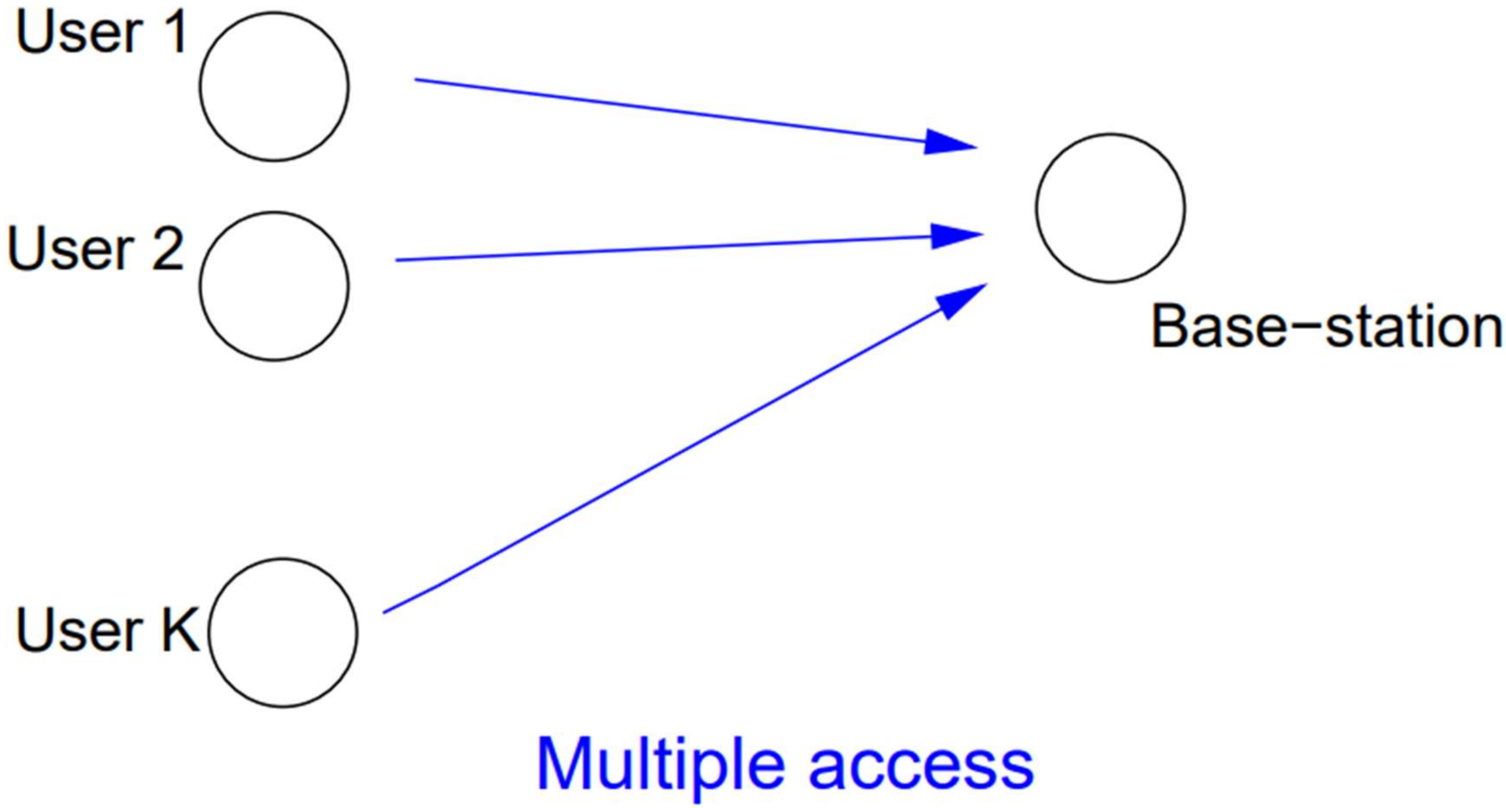
Precoding with partial channel knowledge
Hybrid beamforming

- V. N. Moothedath and S. Bhashyam, "Distributed Pareto Optimal Beamforming for the MISO Multi-band Multi-cell Downlink," in IEEE Transactions on Wireless Communications, vol. 19, no. 11, pp. 7196-7209, Nov. 2020.
- S. S. Nair and S. Bhashyam, "Hybrid beamforming in MU-MIMO using partial interfering beam feedback," in IEEE Communications Letters, vol. 24, no. 7, pp. 1548-1552, July 2020.

Multiuser Communication

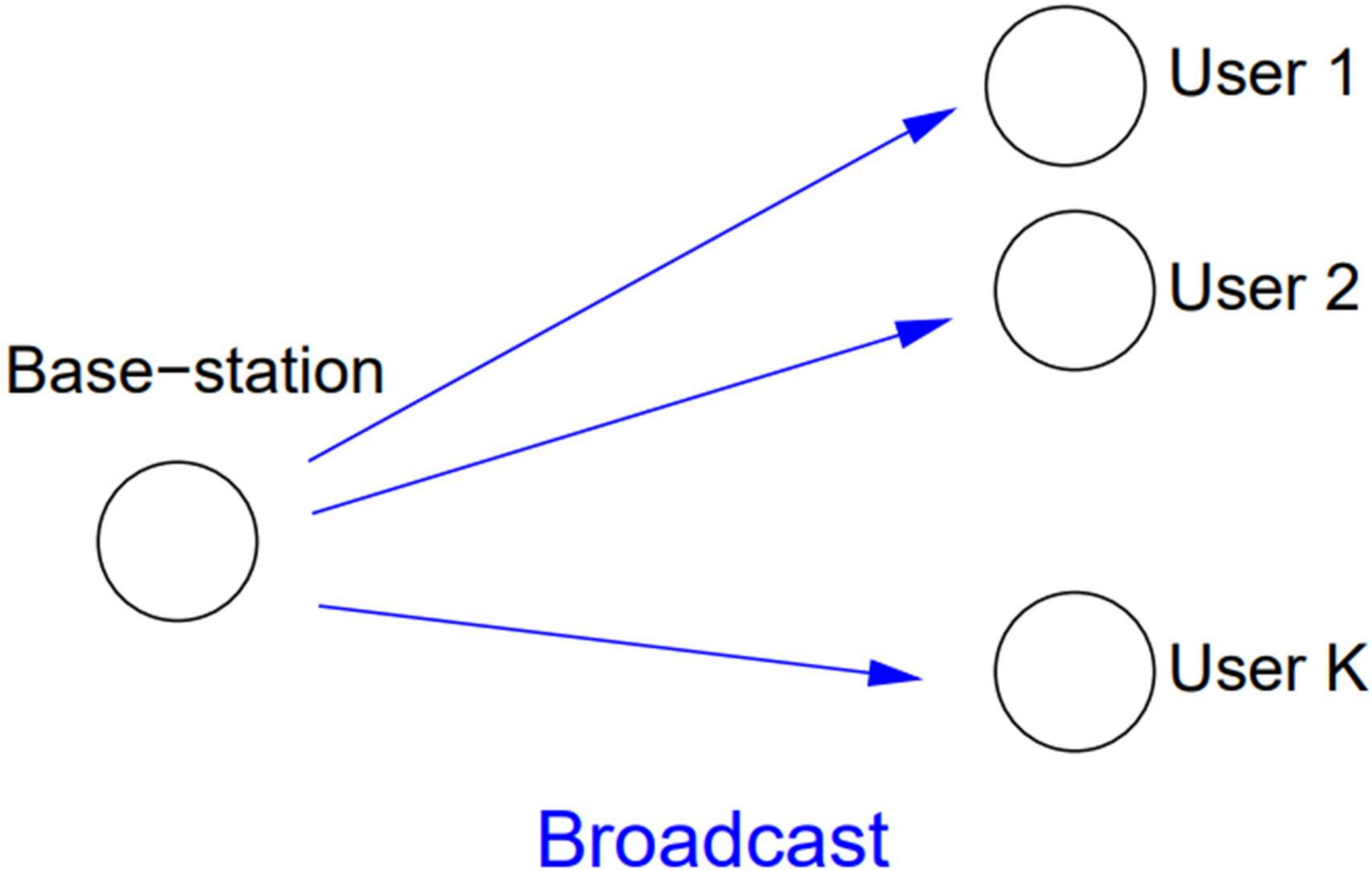
Multiuser channels

- Cellular uplink as a multiple access channel



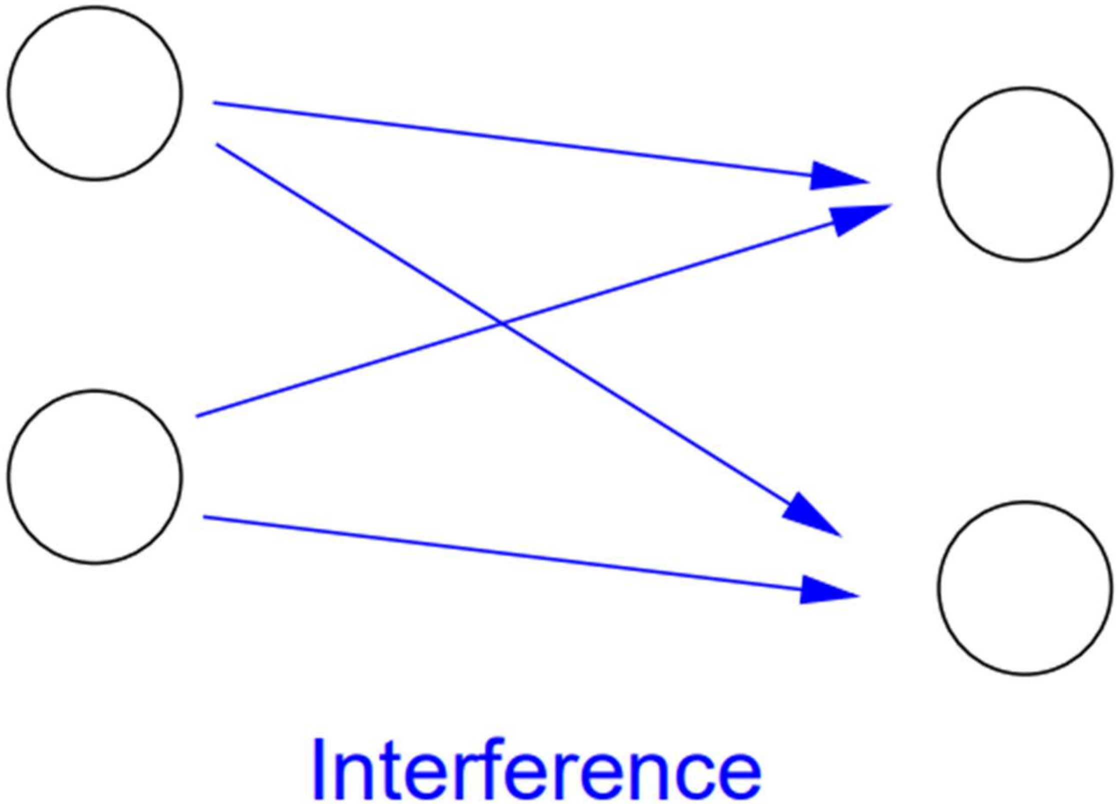
Multiuser channels

- Cellular downlink as a broadcast channel



Multi-cell network

- Interference channel and Interference networks

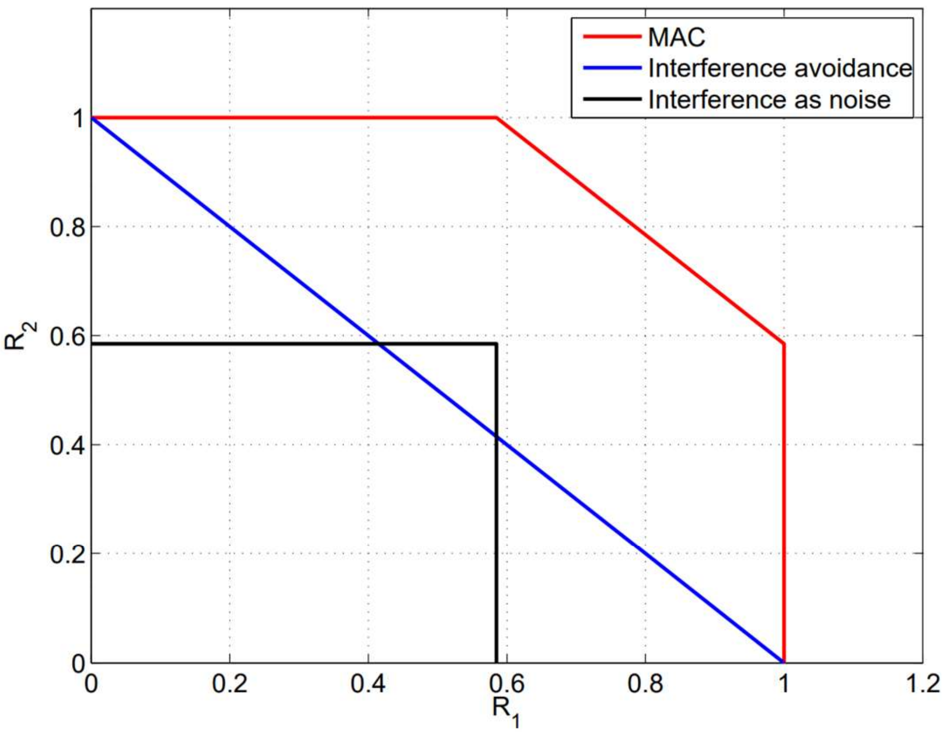


Multiple access in the 90's

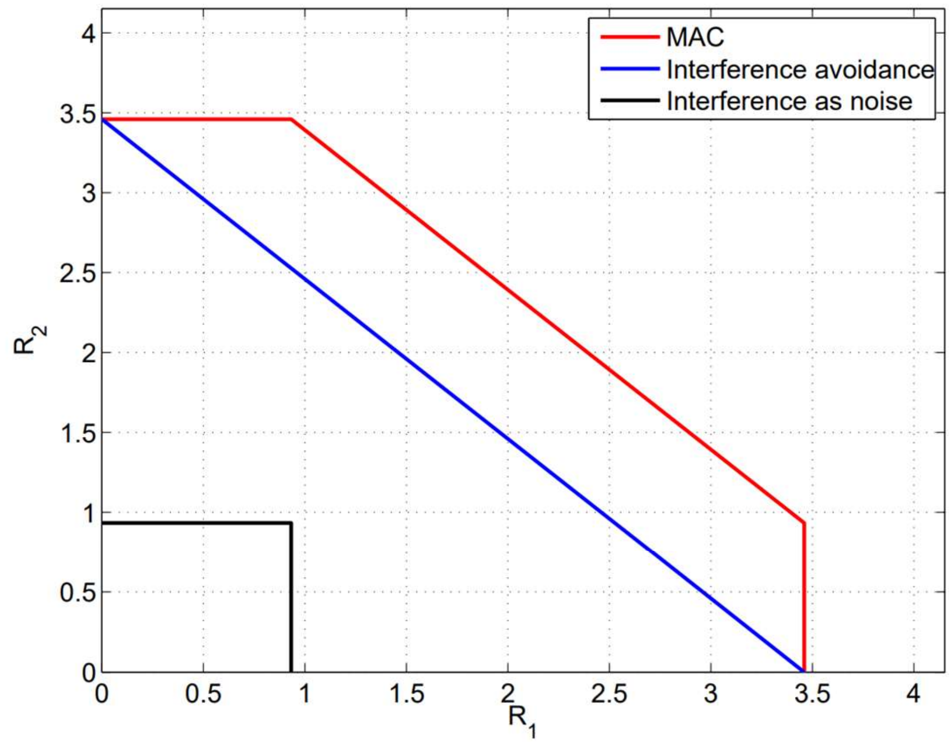
- TDMA/FDMA vs CDMA
- GSM vs. IS-95
  - Frequency planning in GSM
  - Diversity and soft handoff in CDMA
  - Fast power control in CDMA
- Two types of CDMA – Long codes vs. Short codes
- Resource allocated over a call duration

Two-user MAC capacity region

- Gaussian Multiple Access Channel

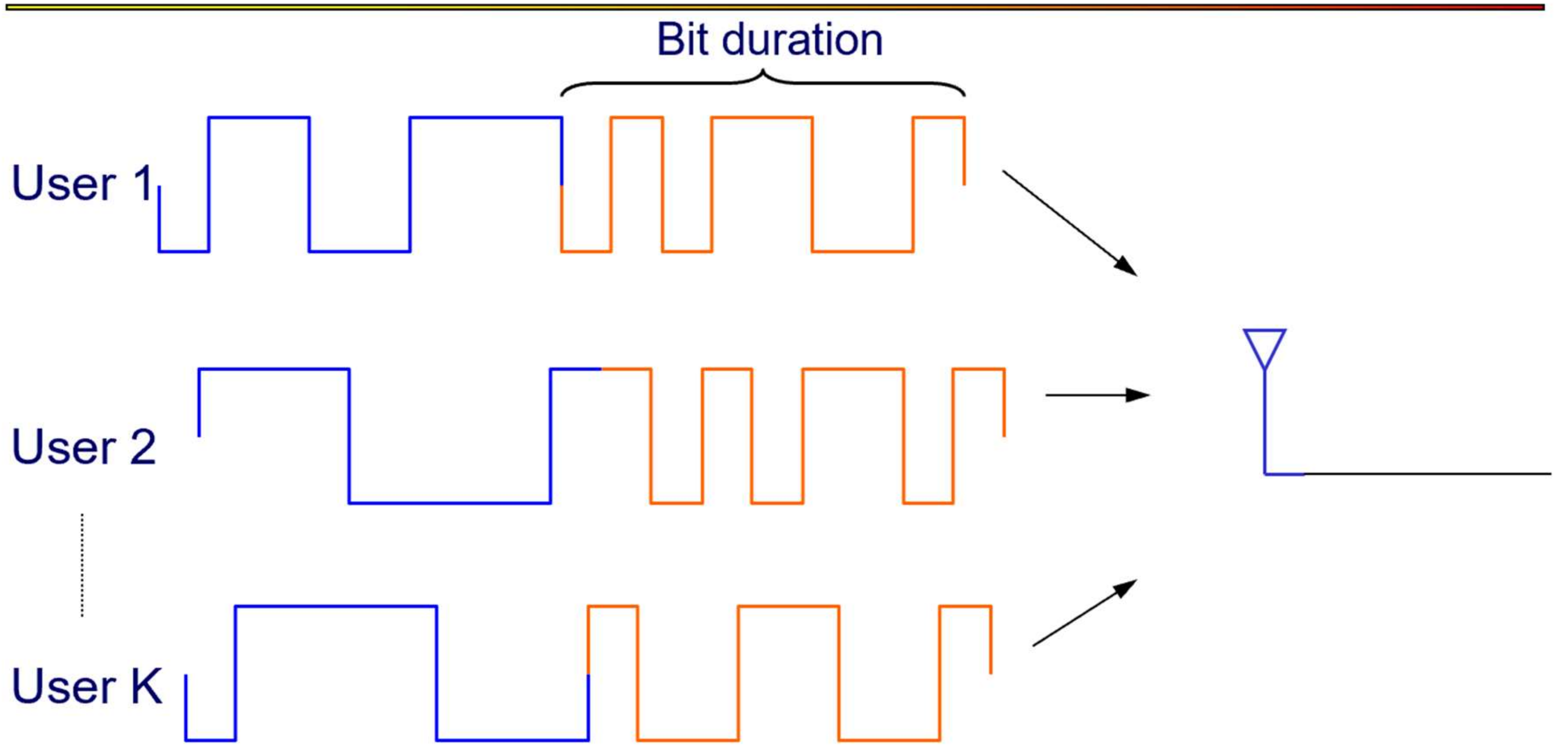


$P_1 = 0$ dB, $P_2 = 0$ dB



$P_1 = 10$ dB, $P_2 = 10$ dB

Long Code CDMA Vs Short Code CDMA



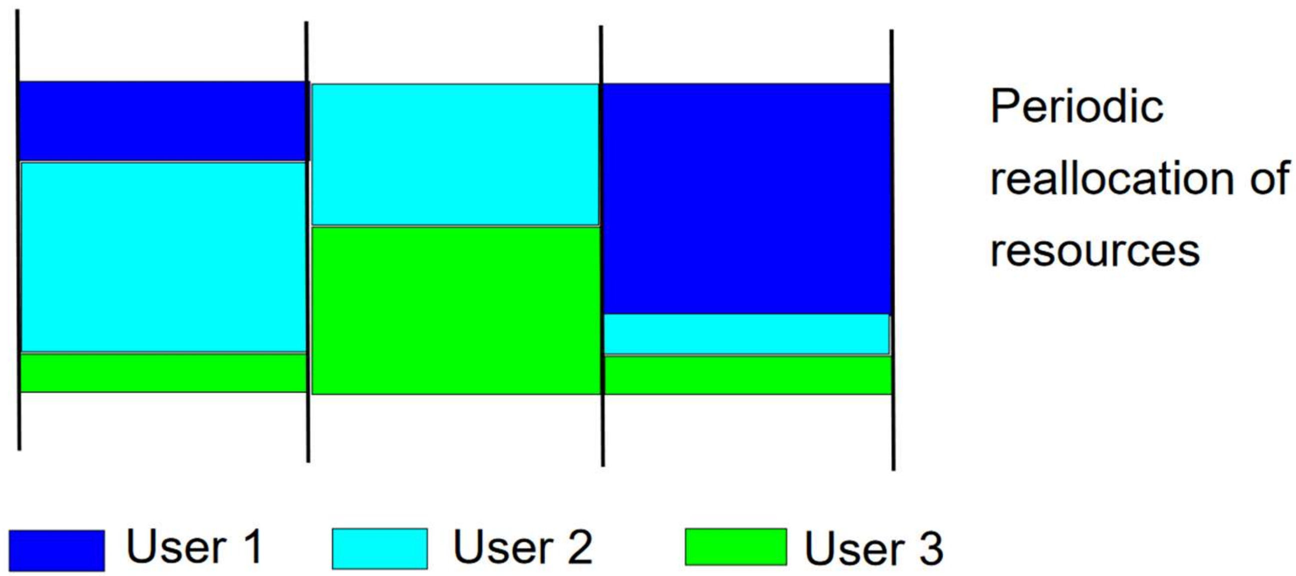
- Short codes: same spreading code for all bits
- Long codes: different spreading code for each bit
- Long codes used in practical systems

S. Bhashyam, B. Aazhang , "Multiuser Channel Estimation and Tracking for Long Code CDMA Systems", IEEE Transactions on Communications, vol. 50, no. 7, pp. 1081-1090, July 2002.

Dynamic Resource Allocation

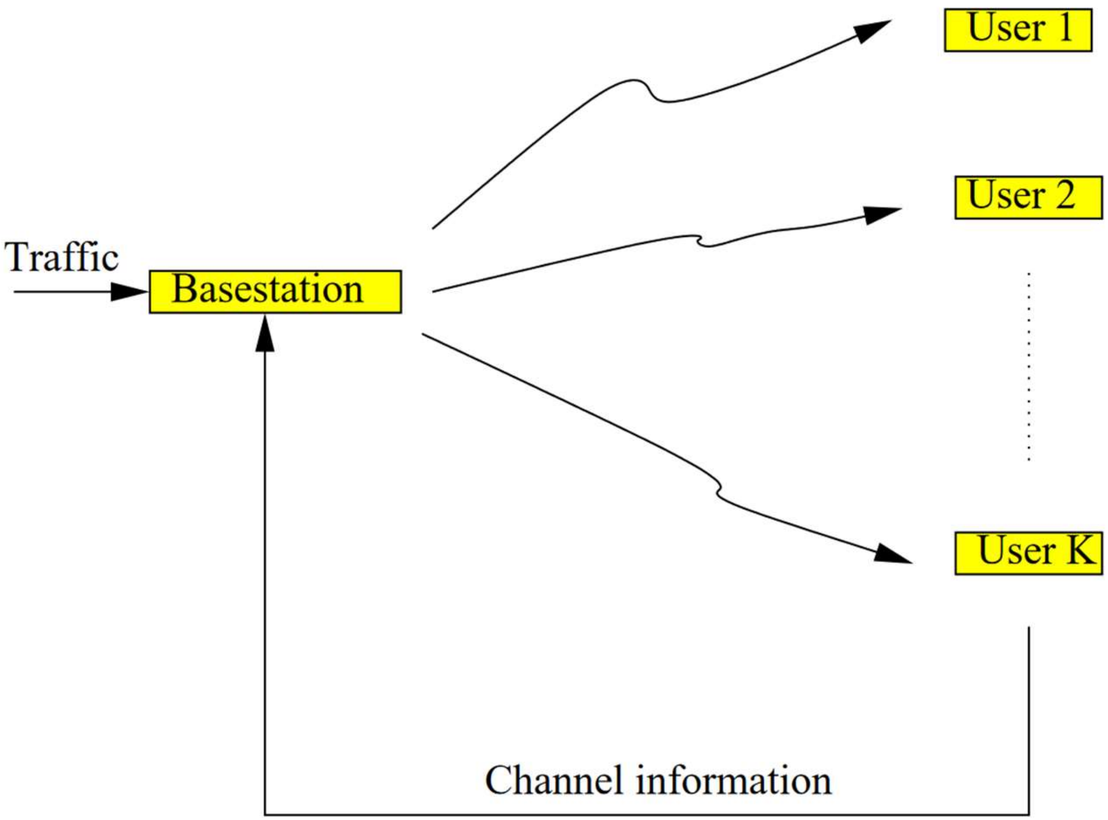
- Packet data transmission became more important
- Need to reallocate resources dynamically based in channel conditions – Multiuser diversity
  - Feedback made this possible
- Adaptive transmission
  - Not much TDMA vs CDMA debate
  - Introduction of HSDPA and HSUPA in 3G
  - OFDM breaks up resources in more flexible manner
- Within each slot, different multi-access schemes do provide different rate vectors

Dynamic Resource Allocation in Cellular Systems



- Adaptation to channel and traffic conditions
- Dynamic resource allocation
  - Reallocation period of the order of a few milliseconds

Cross-layer resource allocation

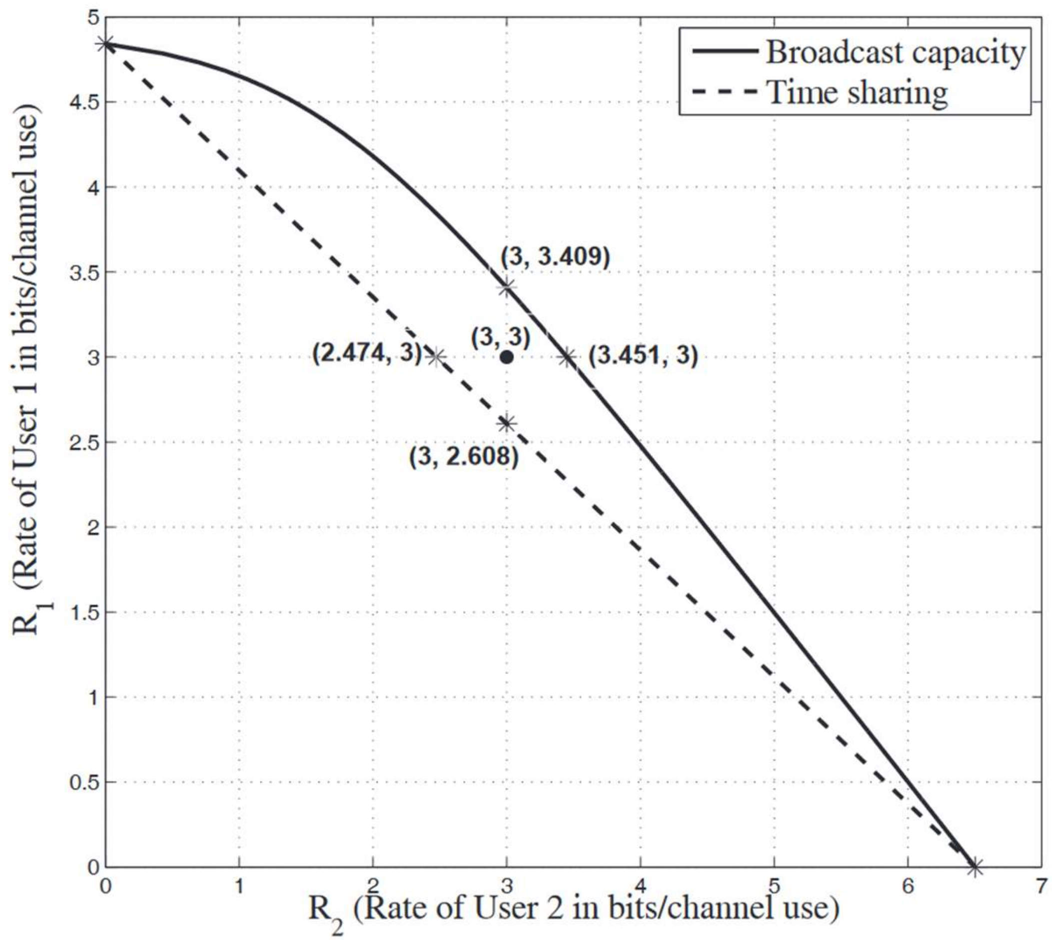


Use channel and queue state information

More transmission modes beneficial

- C. Mohanram, S. Bhashyam, "Joint Subcarrier and Power Allocation in Channel-Aware Queue-Aware Scheduling for Multiuser OFDM," IEEE Transactions on Wireless Communications, vol. 6, no. 9, pp. 3208-3213, September 2007.
- C. Manikandan, S. Bhashyam, R. Sundaresan, "Cross-layer scheduling with infrequent channel and queue measurements," IEEE Transactions on Wireless Communications, vol. 8, no. 12, pp. 5737-5742, December 2009.
- H. Ahmed, K. Jagannathan, S. Bhashyam, "Queue-Aware Optimal Resource Allocation for the LTE Downlink with Best M Sub-band Feedback," IEEE Transactions on Wireless Communications, vol. 14, no. 9, pp. 4923-4933, Sep. 2015.

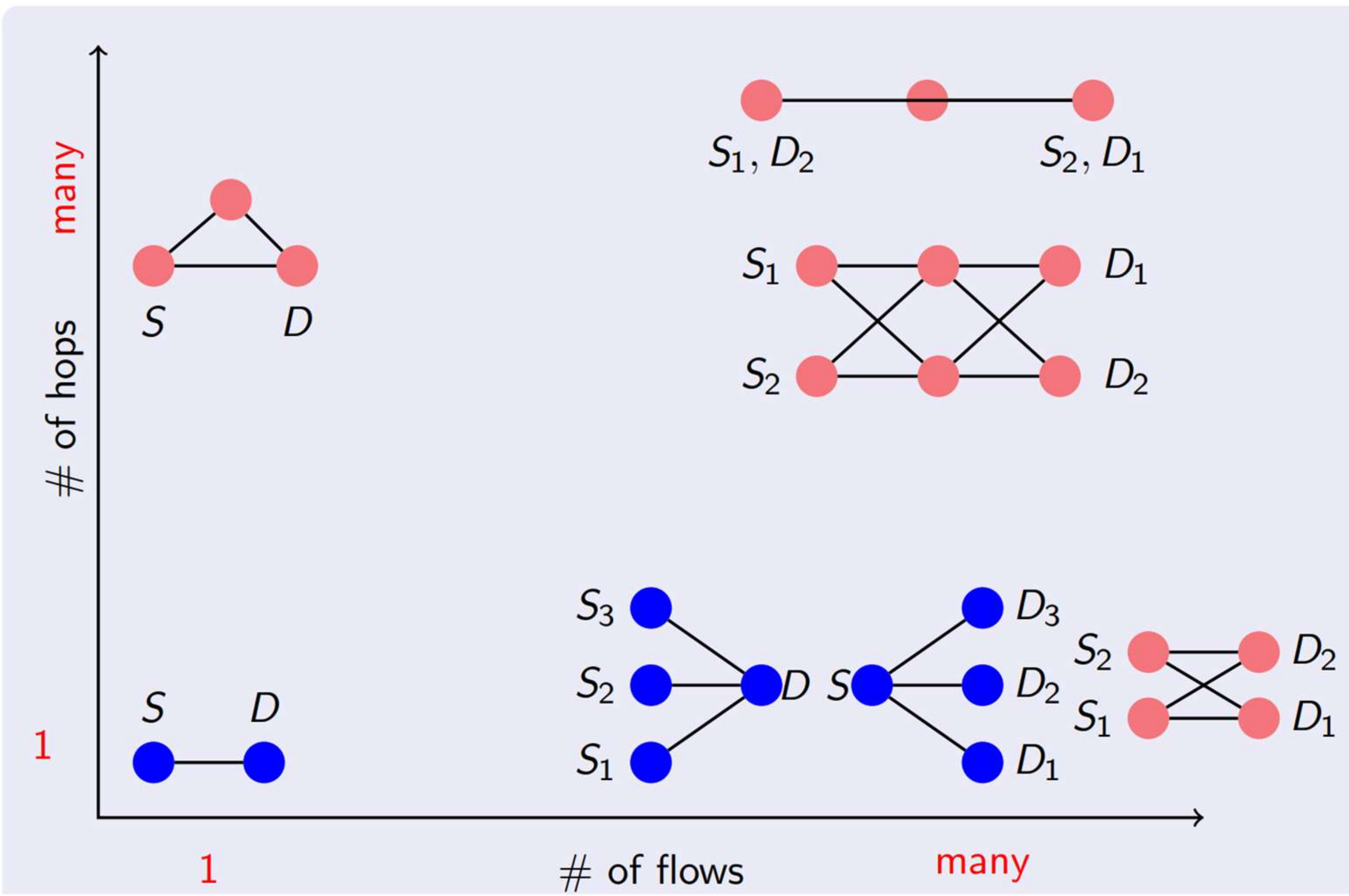
Broadcast channel



- S. Gadiraju, A. Thangaraj, S. Bhashyam, Dirty Paper Coding using Sign-bit Shaping and LDPC Codes, Proceedings of ISIT 2010, pp. 923-927, Austin, Texas, USA, June 13-18 2010.
- B. Saradka, S. Bhashyam, A. Thangaraj, "A Dirty Paper Coding Scheme for the Multiple Input Multiple Output Broadcast Channel," Proceedings of NCC 2012, IIT Kharagpur, India, Feb 2012.

Multi-hop multi-flow networks

Can we understand general networks?



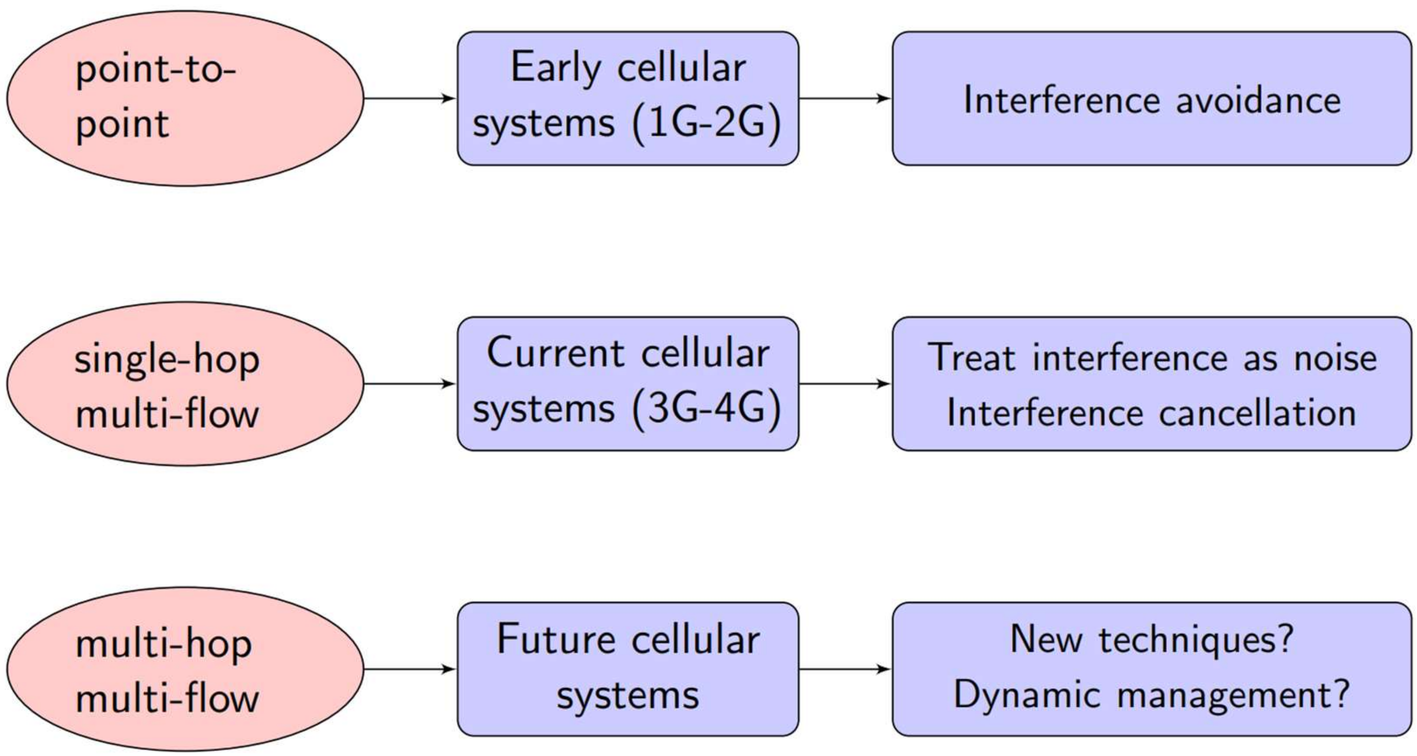
Multiuser communication: Selected work at IITM

- Capacity of multi-hop multi-flow networks
  - MIMO X channel, Many-to-one X channel
  - MIMO Z channel
  - K-user Interference Channel
  - Relay networks: Two-way relaying, Multi-hop relaying

- B. Muthuramalingam, S. Bhashyam, A. Thangaraj, "A Decode and Forward Protocol for Two-stage Gaussian Relay Networks," IEEE Transactions on Communications, col. 60, no. 1, pp. 68-73, January 2012.
- Praneeth Kumar V., S. Bhashyam, "MIMO Gaussian X Channel: Noisy Interference Regime," IEEE Communications Letters, vol. 18, no. 8, pp. 1295-1298, Aug. 2014.
- R. Prasad, S. Bhashyam, A. Chockalingam, "On the Sum-Rate of the Gaussian MIMO Z Channel and the Gaussian MIMO X Channel," IEEE Transactions on Communications, vol. 63, no. 2, pp. 487-497, Feb. 2015.
- R. Prasad, S. Bhashyam, A. Chockalingam, "On the Gaussian Many-to-One X Channel," IEEE Transactions on Information Theory, vol. 62, no. 1, pp. 244-259, Jan 2016.
- R. Chaluvadi, M. Bolli, S. Bhashyam, On the Optimality of Interference Decoding Schemes for K-User Gaussian Interference Channels. Entropy 2019, 21, 1053. Special Issue on Multiuser Information Theory II.
- A. V. Mampilly and S. Bhashyam, "Successive Relaying for Two-hop Two-Destination Multicarrier Relay Channels," IEEE Communications Letters, vol. 24, no. 3, pp. 685-689, March 2020.

Multi-hop multi-flow networks

Evolution of Cellular Systems: Interference viewpoint



2015 slide

Treat network as a network of well-understood building blocks

Summary

- MIMO and multiuser communication
  - Two hot topics: Flurry of activity since 90’s
  - Some important developments, insights, my journey
- Recent work and future directions
  - Sparse recovery for massive random access
  - Sensing-assisted beamforming
  - MIMO-BC with Reconfigurable Intelligent Surfaces
  - MIMO radar
  - Cell-free MIMO