An overview of various physical and MAC layer R&D issues in 4G cellular systems

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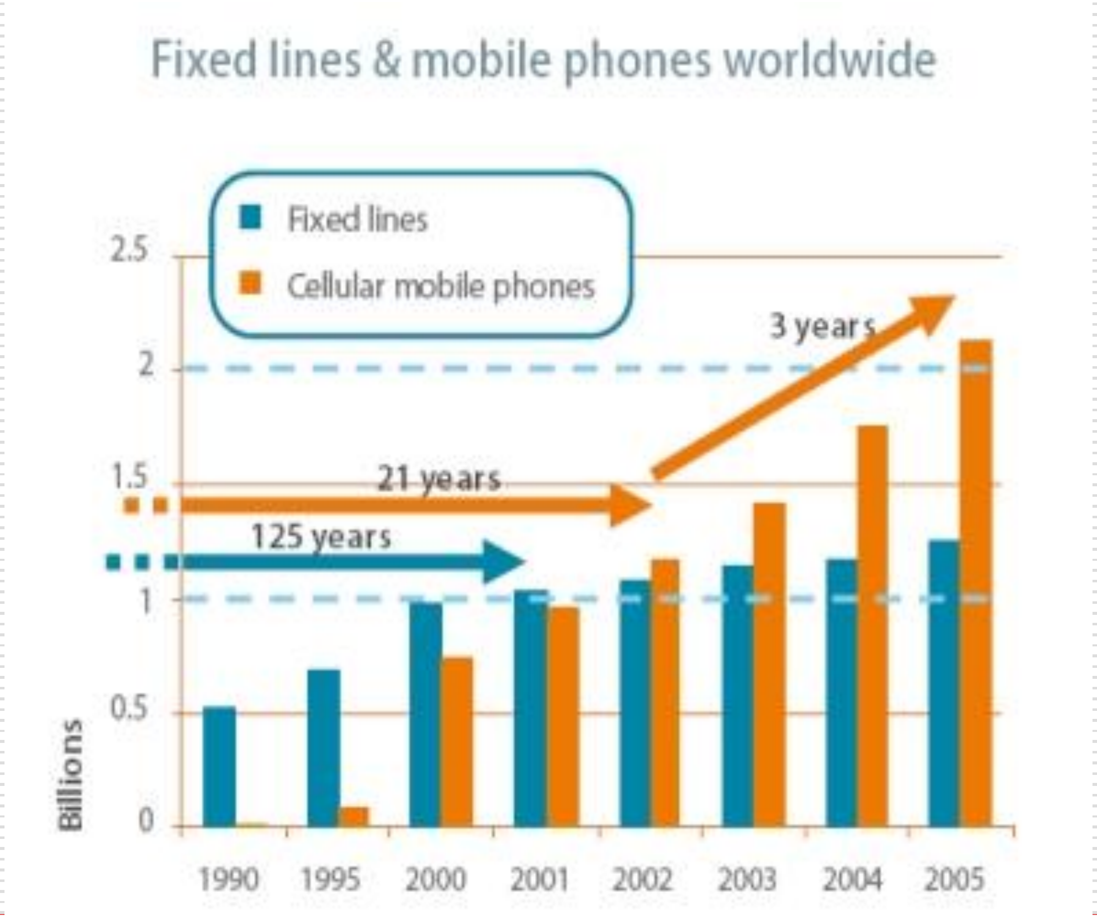
Purpose of this talk

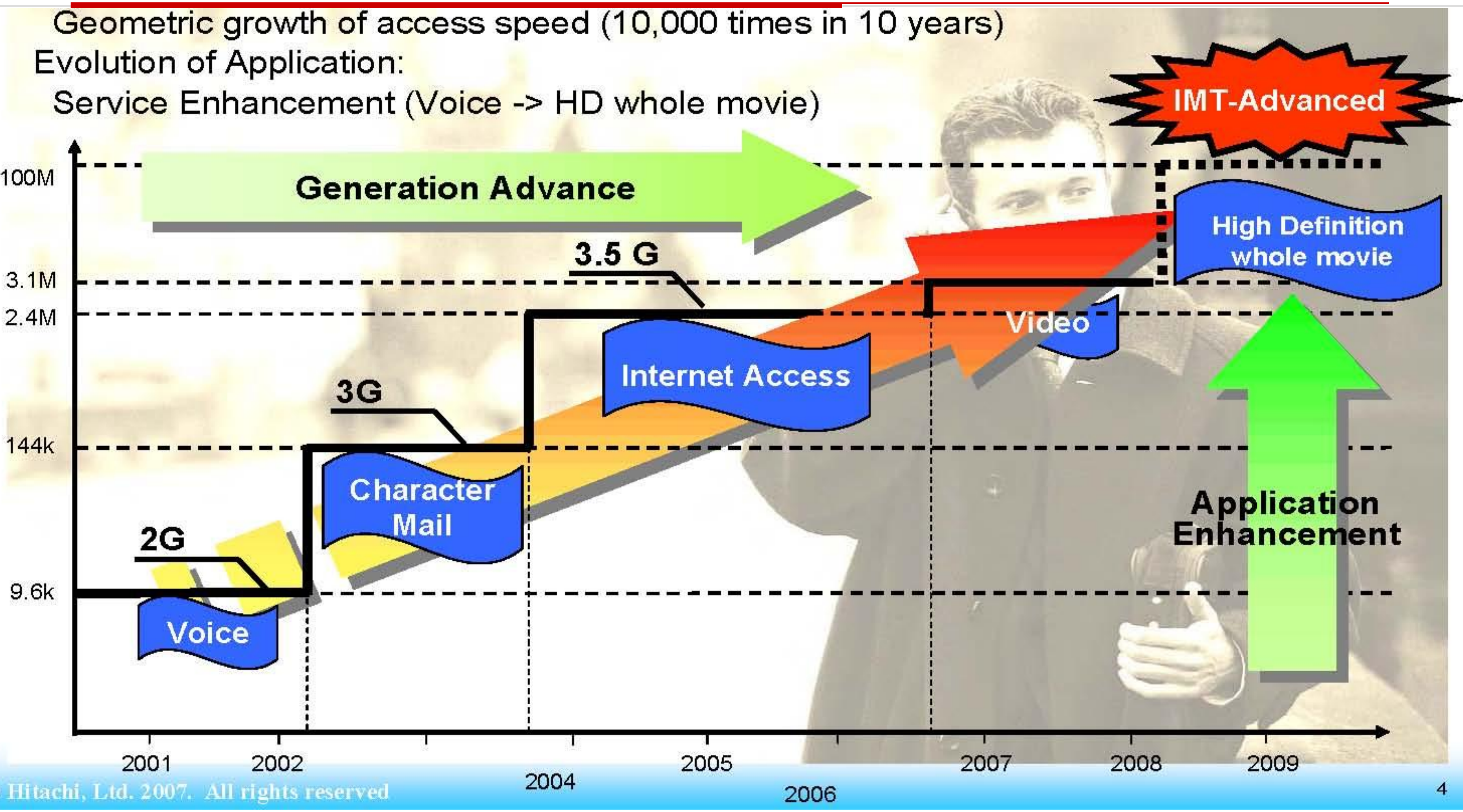
- Wireless communications is in expansion
  - Rapid growth in customer base and new applications
  - Core R&D and their market adoption
- Introduction of key ideas and concepts
  - Physical and MAC layers of cellular systems
- Both technology trends and market dynamics
- Focus on breadth and not depth
- Possible idea exchange/ research collaborations

Some Trends on Subscriber Base

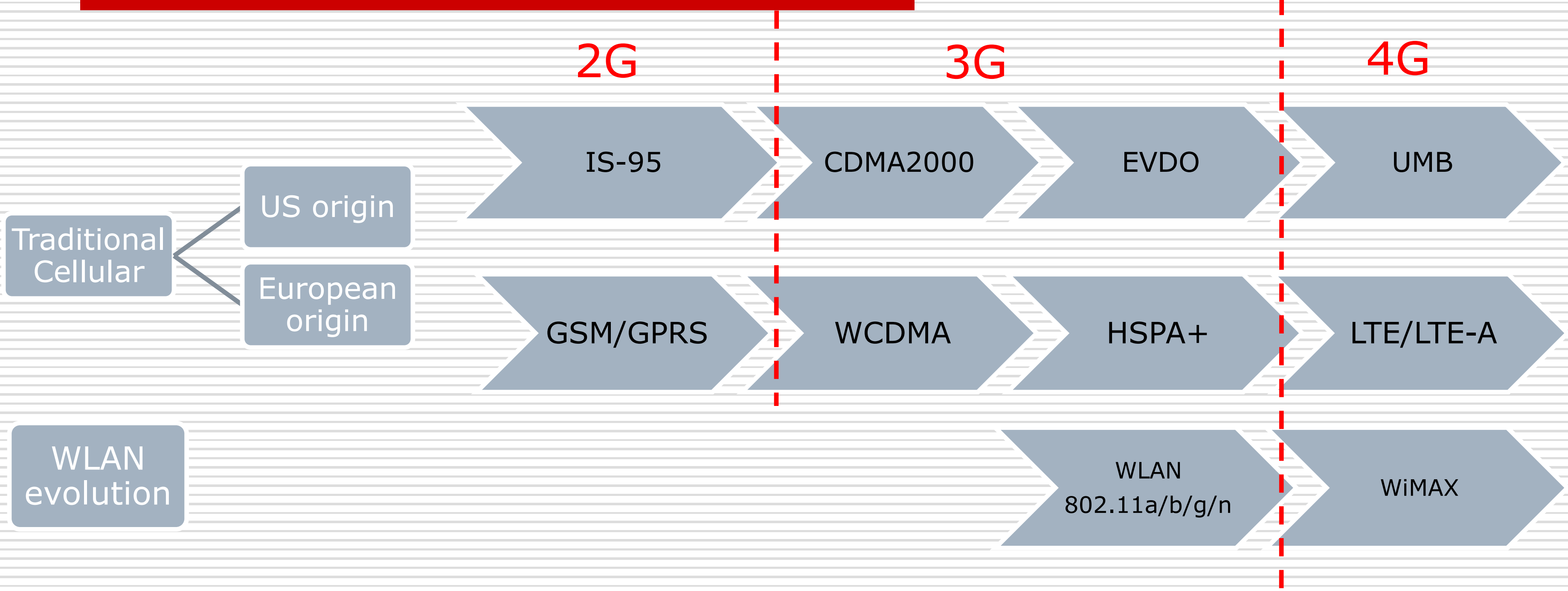


http://www.staygolinks.com/the-whole-world-is-going-mobile.htm

Generations in cellular technology



Cellular Wireless System Evolution



Timeline	Early 1990s	Late 1990s	Mid 2000s+
Rates	O(kbps)	O(Mbps)	O(100 Mbps)
Bandwidth	0.2,1.25 MHz	5 MHz	20 MHz +
Multiple Access	TDMA/FDMA, CDMA	CDMA	OFDMA

How a standard evolves – Part I

- ITU-R (Int. Telecomm. Union Radiocomm. Sector)
  - Releases specifications of next-G systems
  - Done periodically with long term duration, e.g. ~10 years
  - Made of various Govt. bodies
  - Does not specify actual implementation details
- International industry consortiums
  - Decide and standardize exact implementation details
  - **Compatibility needs of mobiles and Base Stations in a network**
    - 3GPP (3rd generation partnership project), 3GPP2, WiMAX Forum
    - Partners are national level consortiums
    - 3GPP partners: ARIB/TTC (Japan), CCSA (China), TTA (South Korea) ETSI (Europe), ATIS (North America)
    - Individual companies are members of one of these partners

How a standard evolves – Part II

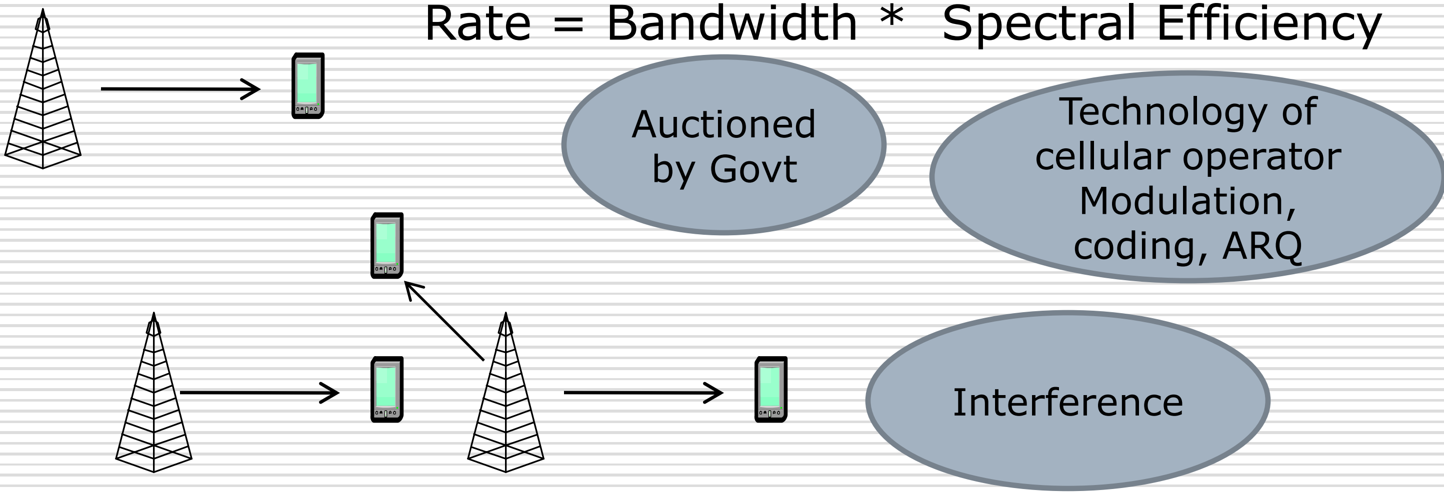
- Meet every 1.5 - 2 months in standard body meetings
- Companies have proprietary solutions for ITU-R specifications
  - E.g. ITU-R specification: 10 Mbps
  - Solutions Company A: a new MIMO spatial mux algorithm, Company B: higher order modulation and coding
- They try to get the interface standardized
  - E.g. Company A will try to standardize use of MIMO
- Often companies collaborate and form cartels
- The most supported technologies are standardized
- How to measure support?
  - WiMAX: Companies vote - each attendee has one vote
  - 3GPP: Consensus system – everyone has to agree

Cellular Systems: Some Features and Ideas

Rate = Bandwidth * Spectral Efficiency

Link Level

System Level



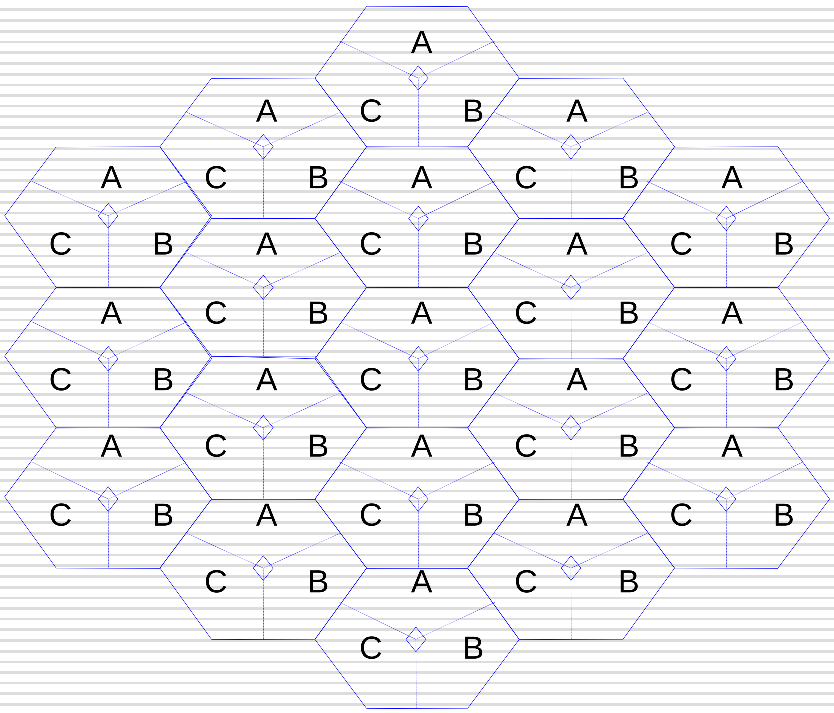
Medium Access: TDMA, FDMA, CDMA, OFDMA

Scheduling: Pick transceiver pair to minimize interference

- System throughput maximization, minimize total transmit power

Advanced DSP: Multiple antenna (MIMO), OFDM, Interference Mitigation

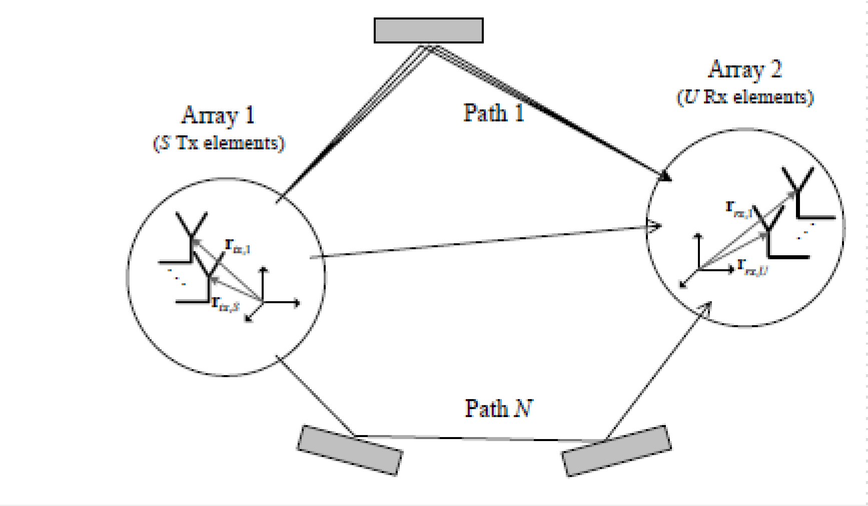
System Level Cellular Model



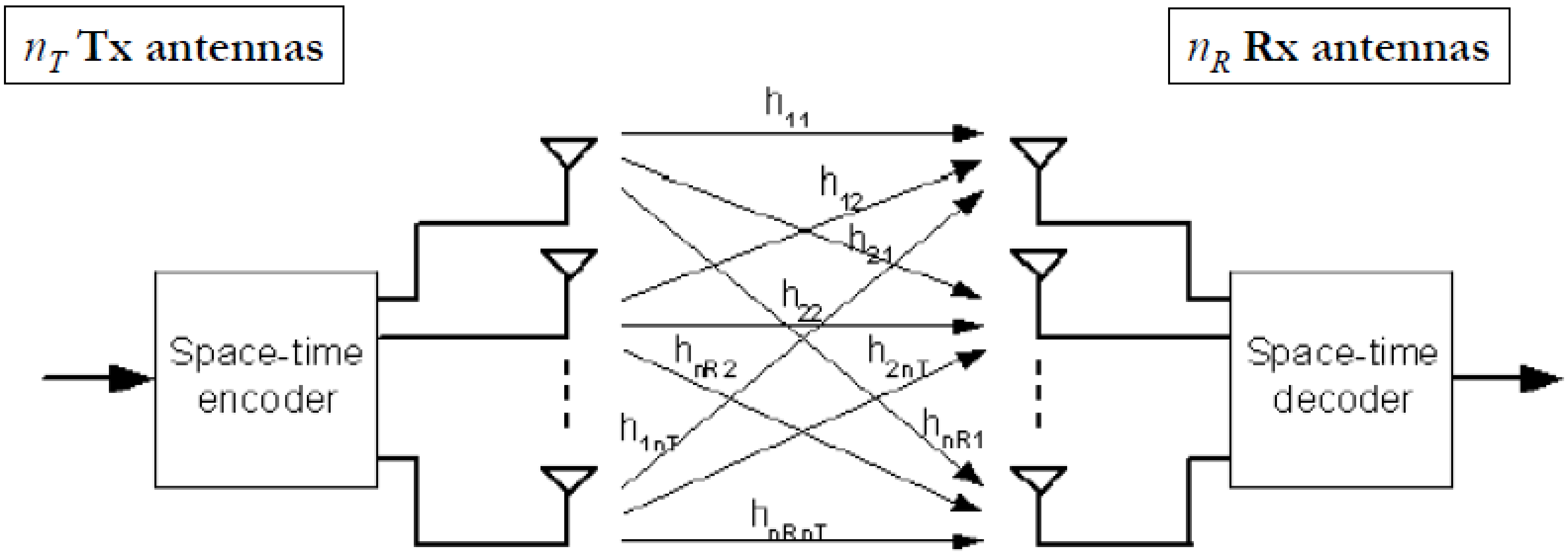
- 19 cell, 3 sectors/cell structure
- This pattern is repeated
- 2 tiers of interferers around each cell
- 20 dB sectorized antenna
- Path loss + shadowing + small scale fading
- Each mobile associates with strongest base station

3GPP Channel Models

- Different environments
  - Urban Microcell, hotspot, rural macrocell
- Empirical path loss models
  - Vary with distance, frequency, antenna height etc.
- Cluster based small scale fading
- Antenna correlations
- Correlations between small and large scale fading parameters and distance
- SCM, WINNER-2 models
- Matlab code public



Basics of MIMO - System Model



$$\begin{bmatrix} y_1 \\ \vdots \\ y_{n_R} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1n_T} \\ \vdots & \ddots & \vdots \\ h_{n_R 1} & \cdots & h_{n_R n_T} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{n_T} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{n_R} \end{bmatrix},$$

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

$$\mathbf{n} \sim N(0, \sigma^2 I)$$

Basics of MIMO - Rate Increase

- Single-input single-output (SISO) Shannon Capacity

$$C = W \log_2 \left(1 + \frac{P}{\sigma^2} \right)$$

Asymptotically,

1 bit/s/Hz every 3 dB

- Instantaneous channel capacity in MIMO (no CSI at Tx)

$$C = W \log_2 \det \left(\mathbf{I} + \frac{P}{n_T \sigma^2} \mathbf{H}\mathbf{H}^H \right)$$

n bit/s/Hz every 3 dB

$n = \min(n_T, n_R)$

- With CSI at Tx, using water-filling

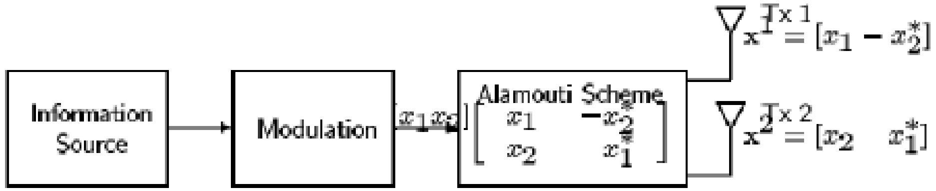
$$C = W \sum_{i=1}^{r} \log_2 \left[1 + \frac{1}{\sigma^2} \left(\lambda_i \mu - \sigma^2 \right)^+ \right], \quad (a)^+ := \max(a, 0)$$

Power allocation: $P_i = \left(\mu - \frac{\sigma^2}{\lambda_i} \right)^+ \quad i = 1, 2, \cdots, r \quad \sum_{i=1}^{r} P_i = P$

- Capacity grows linearly with the number of antennas

Basics of MIMO - More Reliability

- Alamouti scheme for 2 Tx



$$\mathbf{x} = \begin{bmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{bmatrix}$$

- Generalized Orthogonal design for STBC with a large Tx

$$\mathrm{X}\mathrm{X}^{\mathrm{H}} = c\mathrm{I}$$

- Full Diversity gain, no coding gain

- Simple detection with linear algorithms

Basics of OFDM – System Model

- Both a modulation and a multiple access scheme
- Used in LTE, WiMAX, 802.11x
- Data symbols are modulated in sinusoidal carriers

LTI system

$$Y(w) = H(w)X(w) + Z(w)$$

If data is sinusoid $x(t) = e^{iw_0 t}, X(w) = \delta(w - w_0)$

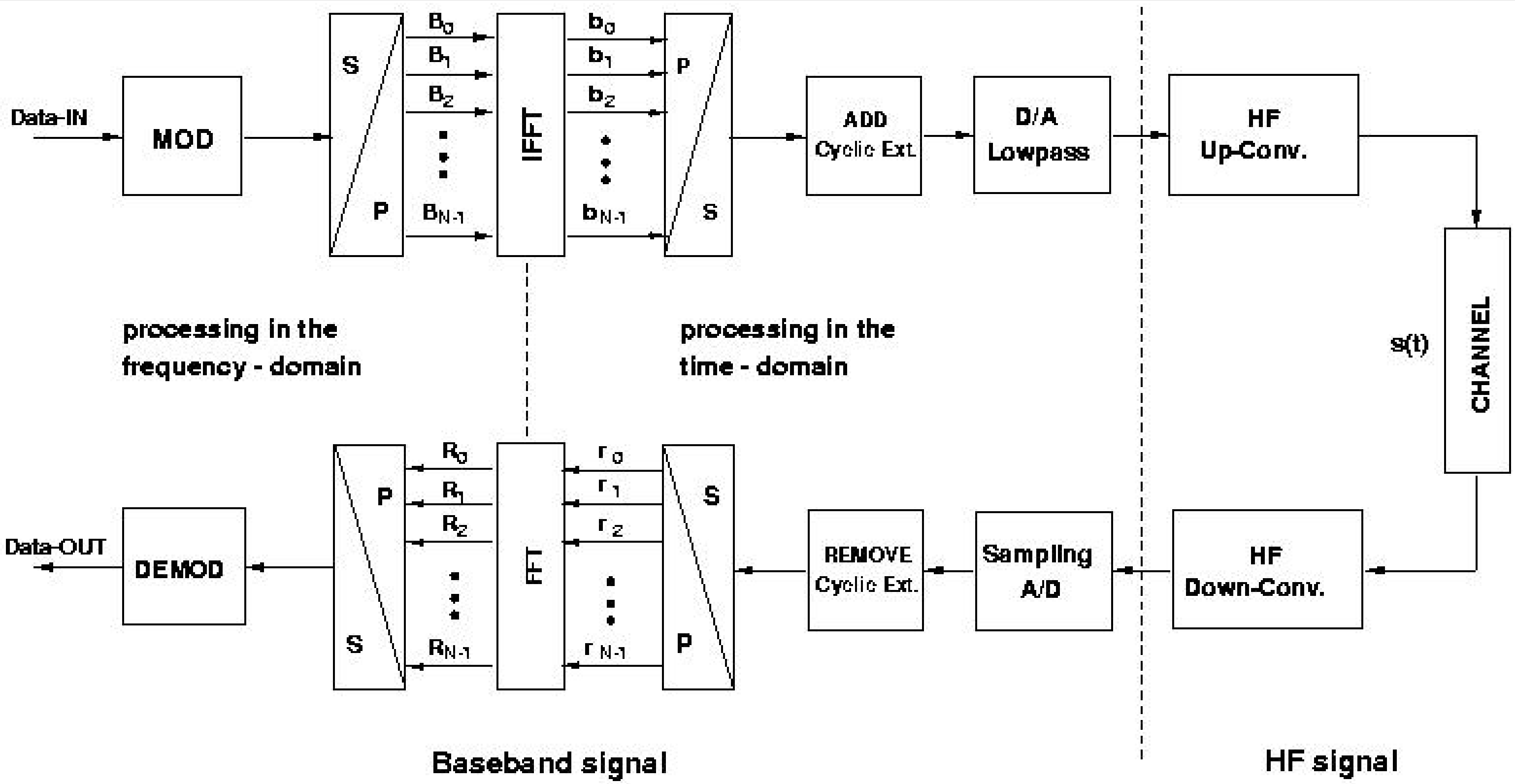
$$Y(w) = H(w_0)\delta(w - w_0) + Z(w)$$

If data is modulated by sinusoids $X(w) = \sum_k \alpha_k \delta(w - w_k)$

$$Y(w) = \sum_k \alpha_k H(w_k)\delta(w - w_k) + Z(w)$$

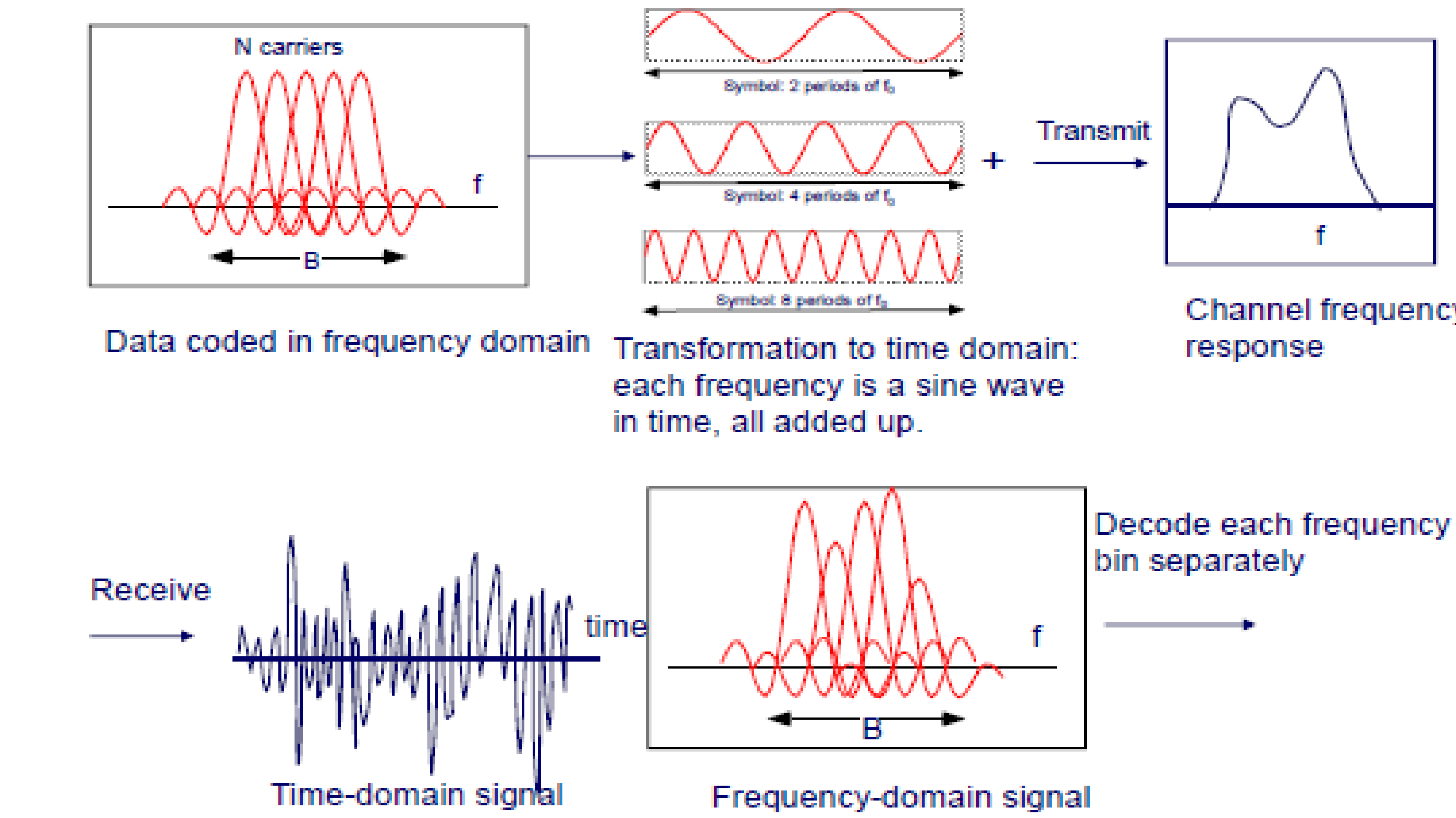
- Exponentials are eigenfunctions of LTI systems
- Conceptually related to FDMA but done digitally using FFT

System Diagram

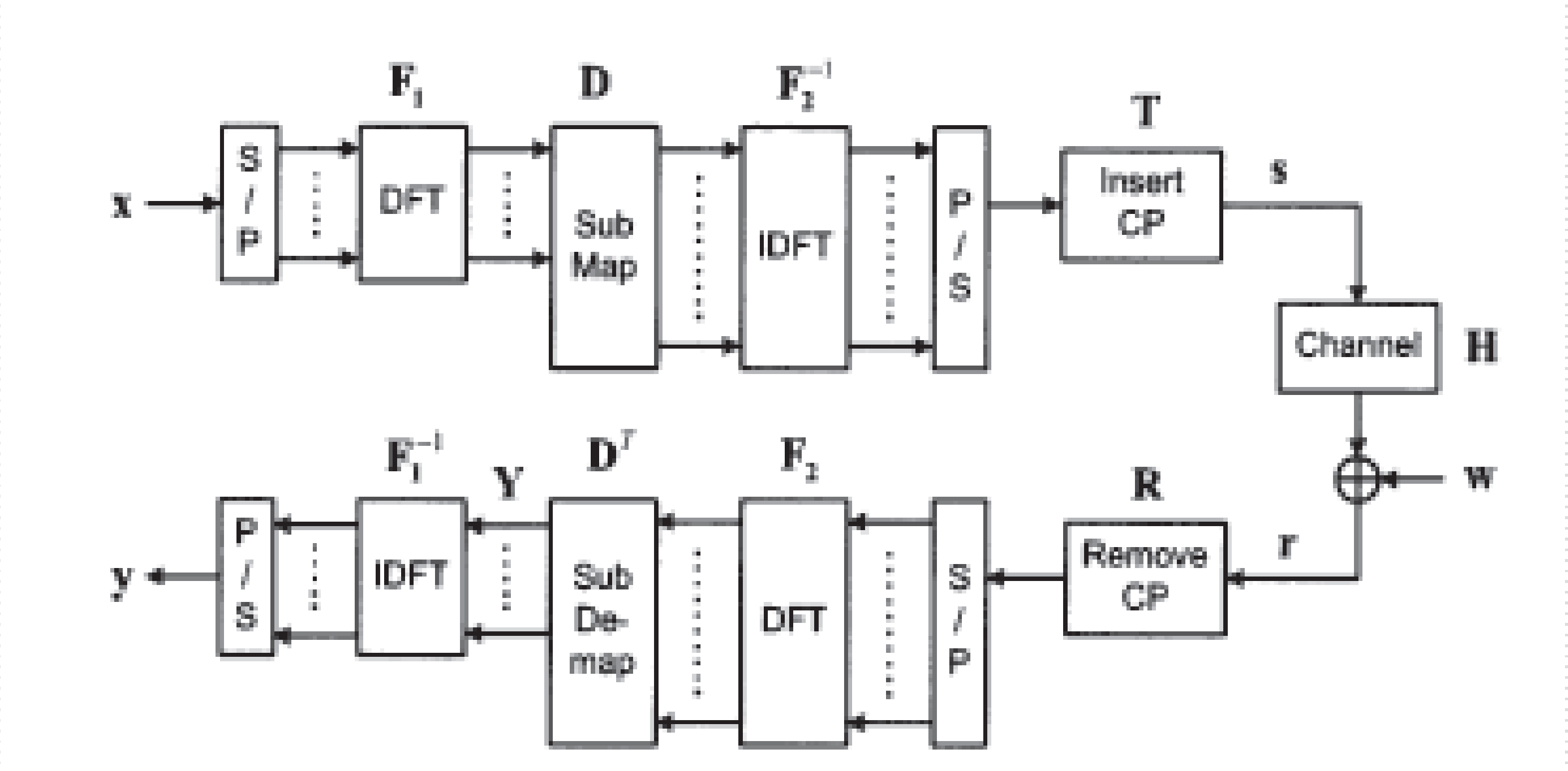


No need for separate analog filters
Fully tunable digitally

OFDM graphical illustration

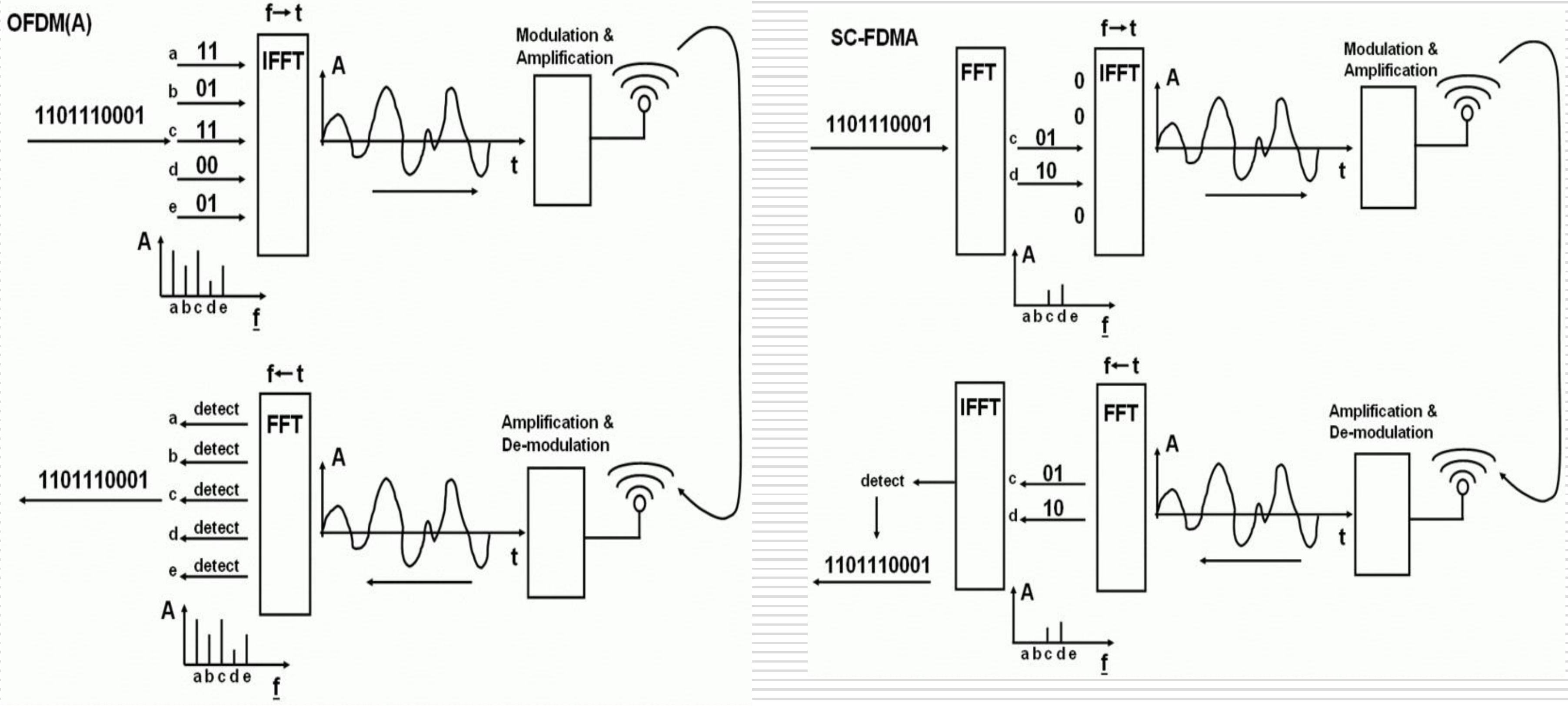


SC-FDMA

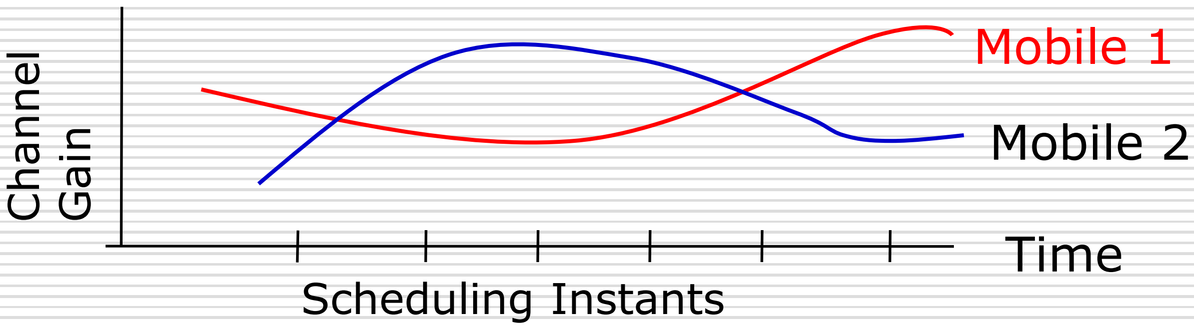


Used in LTE uplink and has an extra DFT/IDFT operation at Tx/Rx

Conceptual Diagram showing difference



Single User Systems: Scheduling



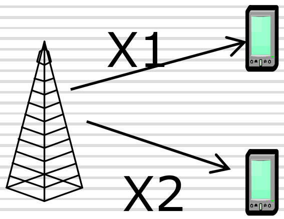
- LTE is single user system
- Schedule mobile who will achieve highest rate R(t) at instant t
- Not fair if one mobile has consistently high channel gain
- Schedule mobile with highest value of $R(t)/R_{avg}(t)$

- $R_{avg}(t) = a*R(t) + (1-a)*R_{avg}(t-1)$ where $0 < a < 1$
- Used in CDMA/HDR systems (Proportional Fair Scheduling)
- Other scheduling metrics: Queue length alone/combined with rate

- Fading is good: Multiuser diversity

Downlink (DL) MIMO operations in LTE and LTE-Advanced

- LTE has SU-MIMO (single user)
  - BS schedules one mobile each time interval (PF schedulin)
  - BS does MIMO signal processing (Spatial Mux, beamforming etc.)
- LTE-A has MU-MIMO (multi user)
- BS schedules 2+ mobiles per interval; transmits to them simultaneously
- Instance of a broadcast channel in information theory



X1 and X2 are desired signals of the mobiles

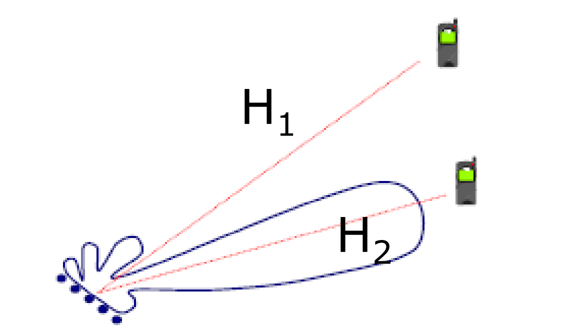
X2 is interference for mobile 2 and vice versa

What are theoretical rates achievable and what are practical transmission schemes ?

Information and communication theory give clues

Zero-Forcing, Dirty Paper Coding, Beamforming

DL MU-MIMO Algorithms



- Beamforming

  Tx non-intefering beams to mobiles

- Block Diagonalization

  Generalization of Zero Forcing for single antenna systems

  BS transmits $S_1X_1 + S_2X_2$ where S_1, S_2 are precoders

  Rx Signal: Mobile 1 - $H_1(S_1X_1 + S_2X_2)$,

  Mobile 2 – $H_2(S_1X_1 + S_2X_2)$

  Design precoders such that $H_1S_2 = 0$ and $H_2S_1 = 0$ (nullspace)

  Effective channels seen are H_1S_1 and H_2S_2 for the mobiles

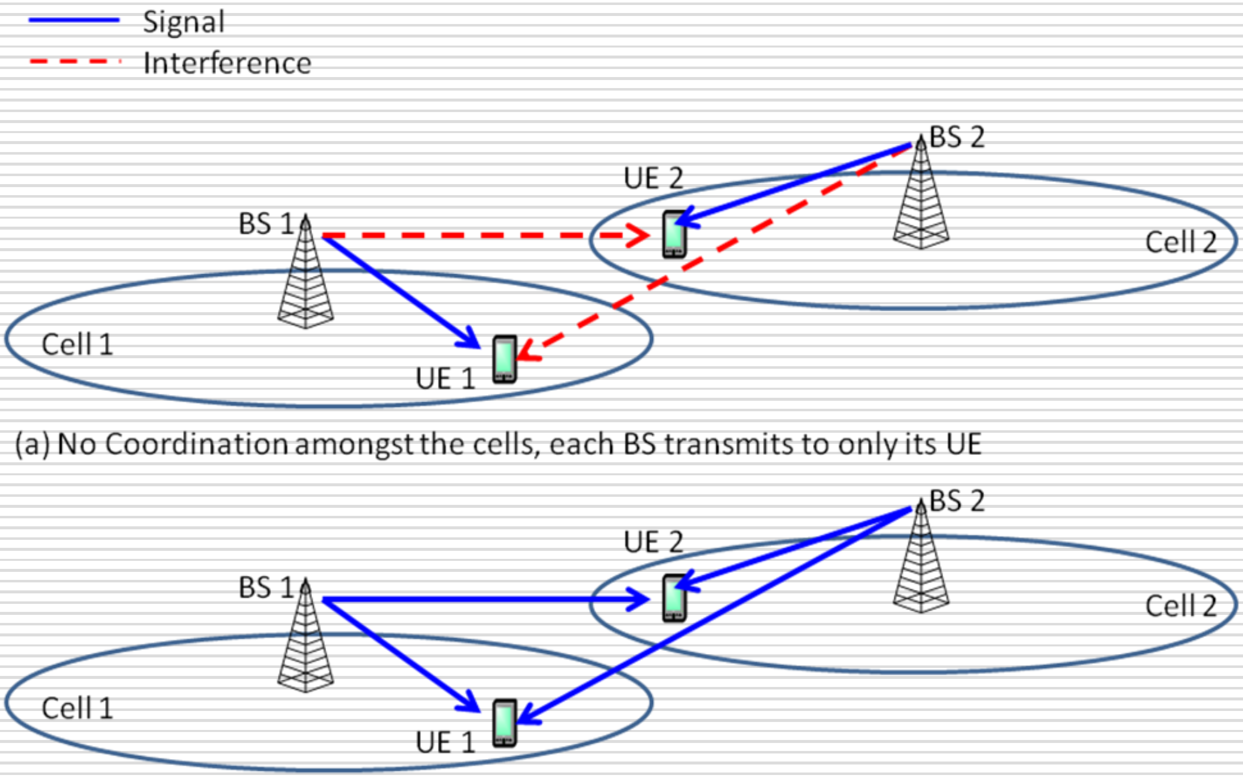
- Dirty Paper Coding (DPC)

  Non linear method based on interference pre-cancellation

  One mobile sees no interference from the other

Base Station Coordination (CoMP)

- Can adjacent base stations cooperated to Tx to their mobiles ?

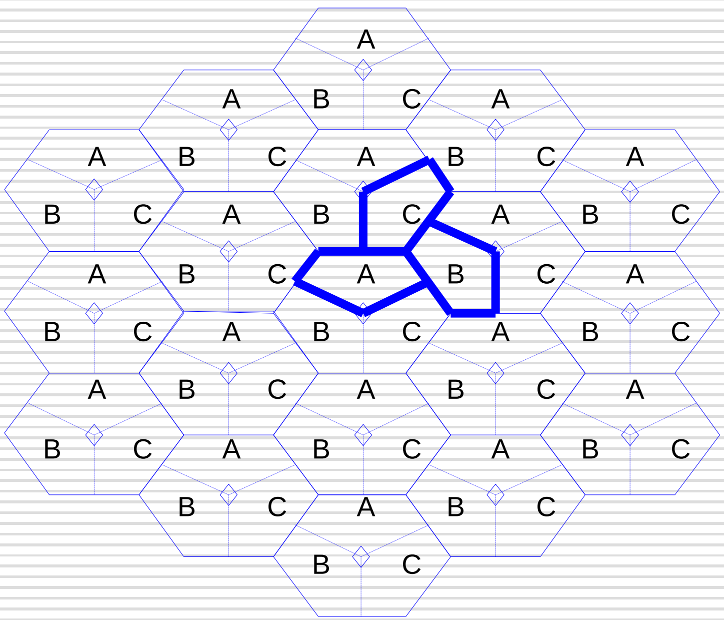


(a) No Coordination amongst the cells, each BS transmits to only its UE

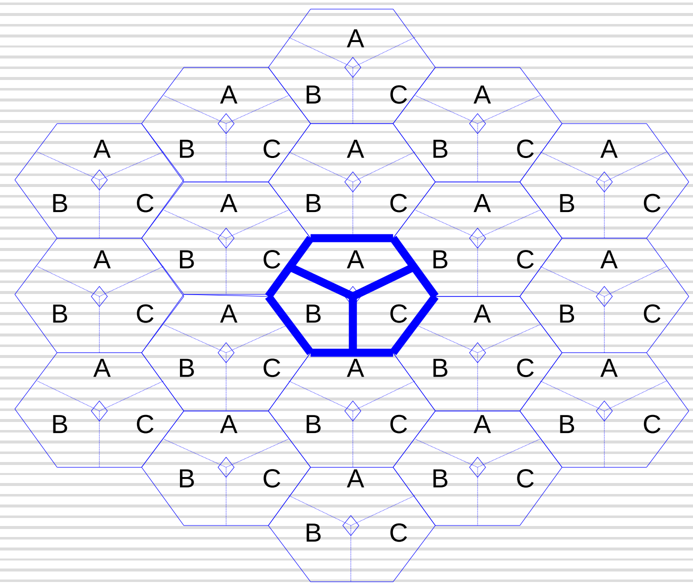
(b) Coordination amongst the cells, each BS transmits to both UEs

Cooperating Set (Cluster) Size

3 Sectors of same cell cooperate



3 Sectors of adjacent cells cooperate



Reduces computation complexity – not all cells cooperating

Inter Cluster interference is still present

Statistical properties of this interference is different from no cooperation case

Other Issues

- Till now focus was on PHY and MAC
- Network and application issues are important
- All IP core
- Security
- Roaming/Handoff
- Heterogeneous networks
- Femto Cells – in home networks in same frequency as macro-cells

Conclusion

- Cellular wireless communication is experiencing rapid growth
- New technologies, features and services
- Many unsolved R&D problems
- Core theoretical principles (MIMO, OFDM etc.) lead to practical systems
- Practical constraints of these systems leads to new R&D opportunities
- Timeline: LTE (2010), LTE-A (2015)