Lecture 3
Cellular Systems

I-Hsiang Wang
ihwang@ntu.edu.tw

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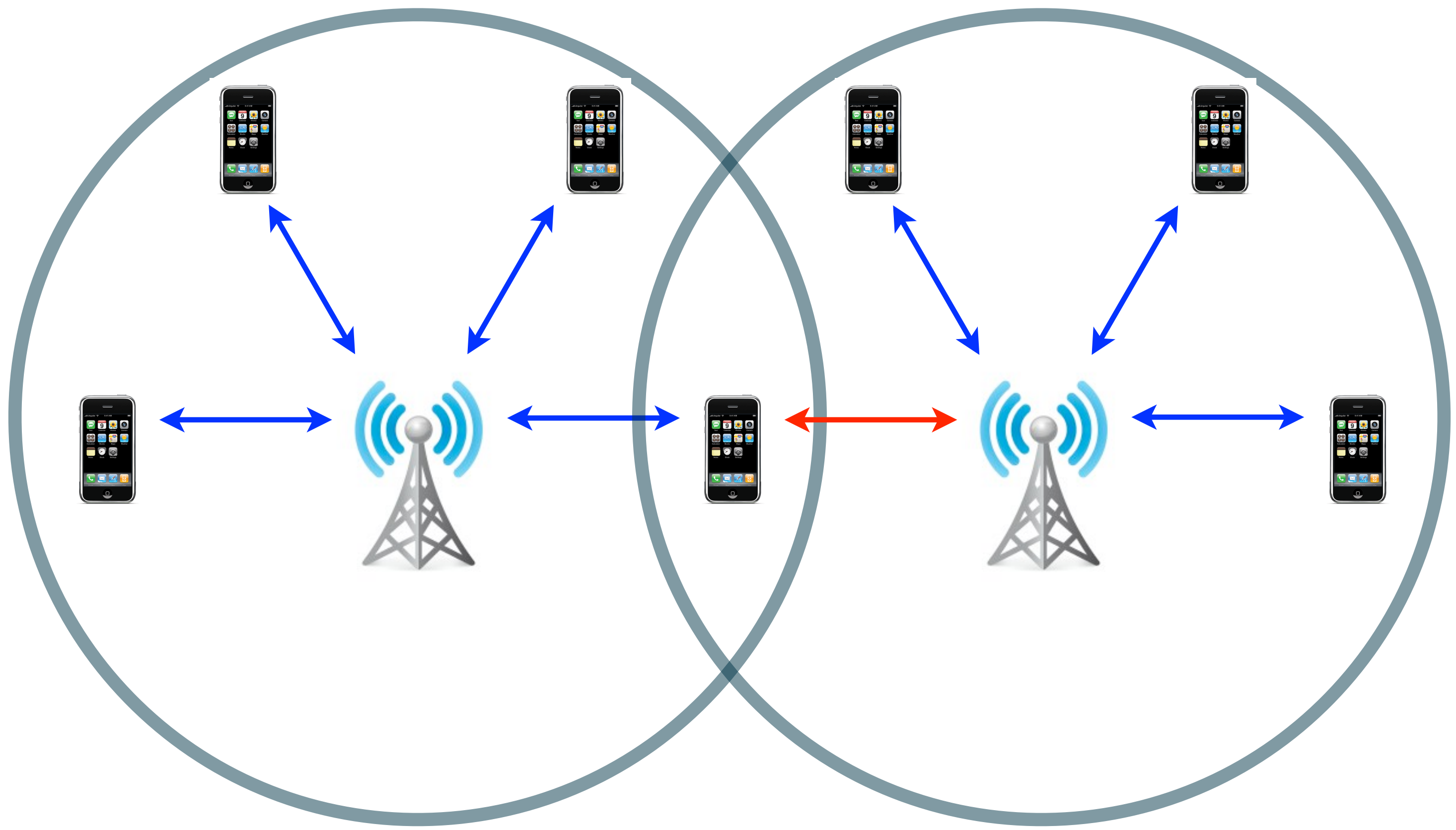
Cellular Systems: Additional Challenges

- So far: focus on point-to-point communication
- In a cellular system (network), additional issues arise:

Multiple access



Inter-cell interference management

Issues Less Emphaized in the Lecture

- Handoff (focus of the network layer)

  기지국1 $\xrightarrow{\text{이동}}$ 기지국2 기지국을 옮겨서 연결하는 경우.

- Duplexing between uplink and downlink:
  - Frequency Division Duplex (FDD)
  - Time Division Duplex (TDD)
- Sectorization
- Focus mainly on licensed cellular systems
  - WiFi, various wireless personal communication systems, are not discussed here

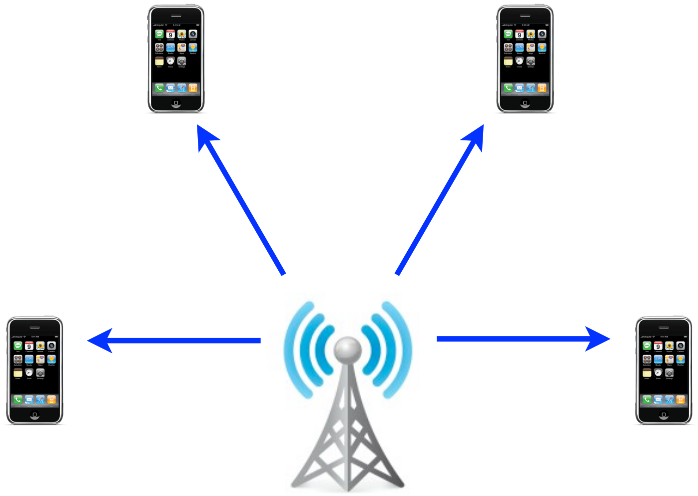
Some History

- Cellular concept (Bell Labs, early 70's)
- AMPS (analog, early 80's)
- GSM (digital, narrowband, late 80's)
- IS-95 (digital, wideband, early 90's)
- 3G/4G systems

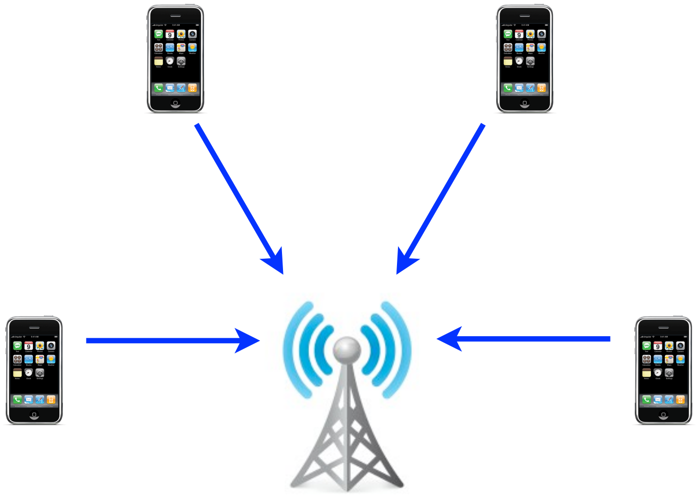
Plot

- Three cellular system designs as case studies to illustrate approaches to multiple access and (inter-cell) interference management

- Both uplink and downlink will be mentioned



Downlink



Uplink

Outline

- Narrowband (GSM)
- Wideband system: CDMA (IS-95, CDMA 2000, WCDMA)
- Wideband system: OFDMA (Flash OFDM, LTE)

OFDM+ FDMA.

Narrowband Systems

Basic Ideas

- Total bandwidth divided into narrowband sub-channels
  - GSM: 25 MHz → 200 kHz × 125 sub-channels
  - Uplink (890 – 915 MHz) and Downlink (935 – 960 MHz): the same

frequency로 나누면 FDMA.

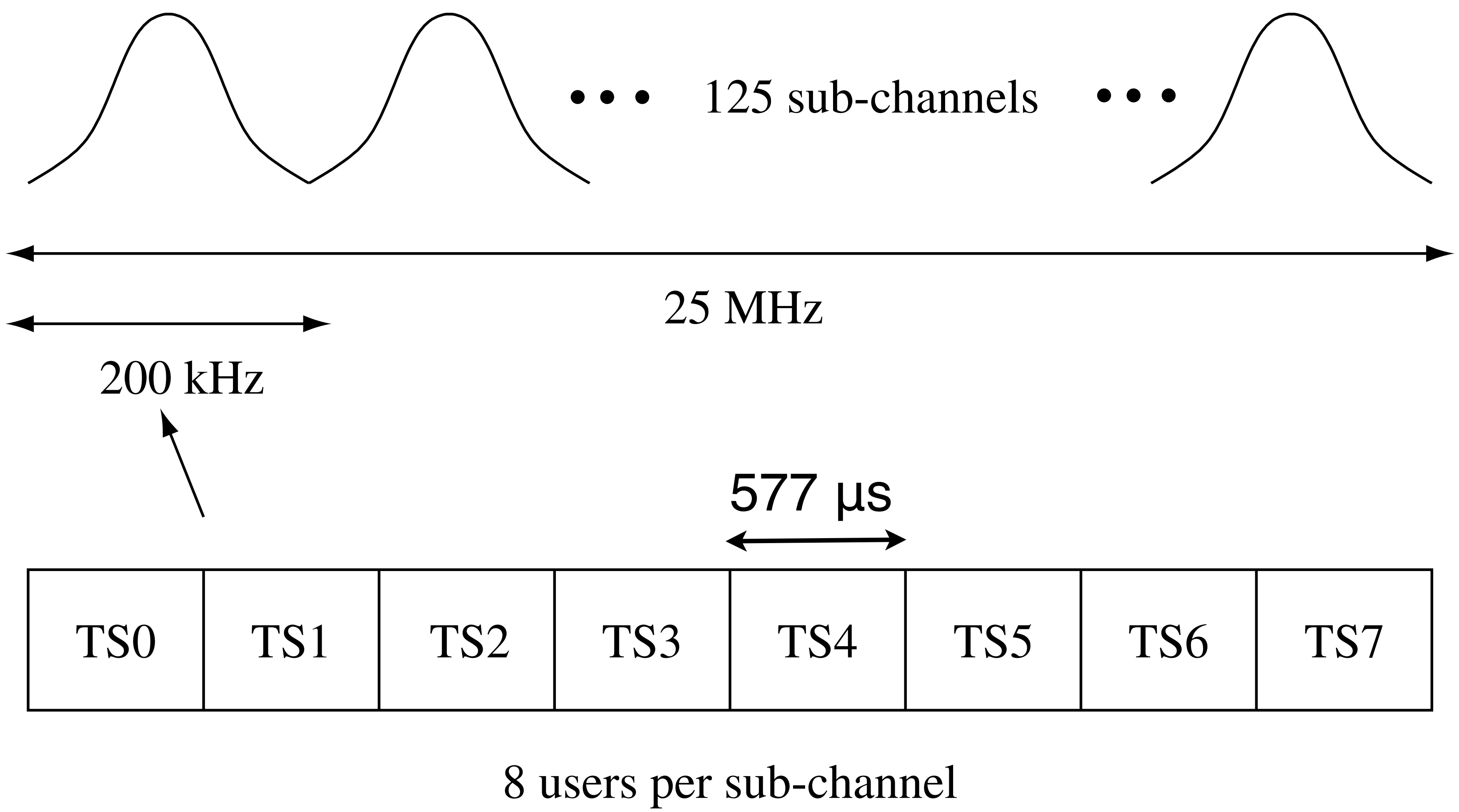
- Time Division Multiple Access (TDMA)
  - Users share time slots in a sub-channel; each user per time slot
  - Multiple access is orthogonal: intra-cell users never interfere with each other

간섭이 거의 없음

- Partial Frequency Reuse
  - Neighboring cells uses disjoint sets of sub-channels
  - Careful frequency planning → essential no inter-cell interference

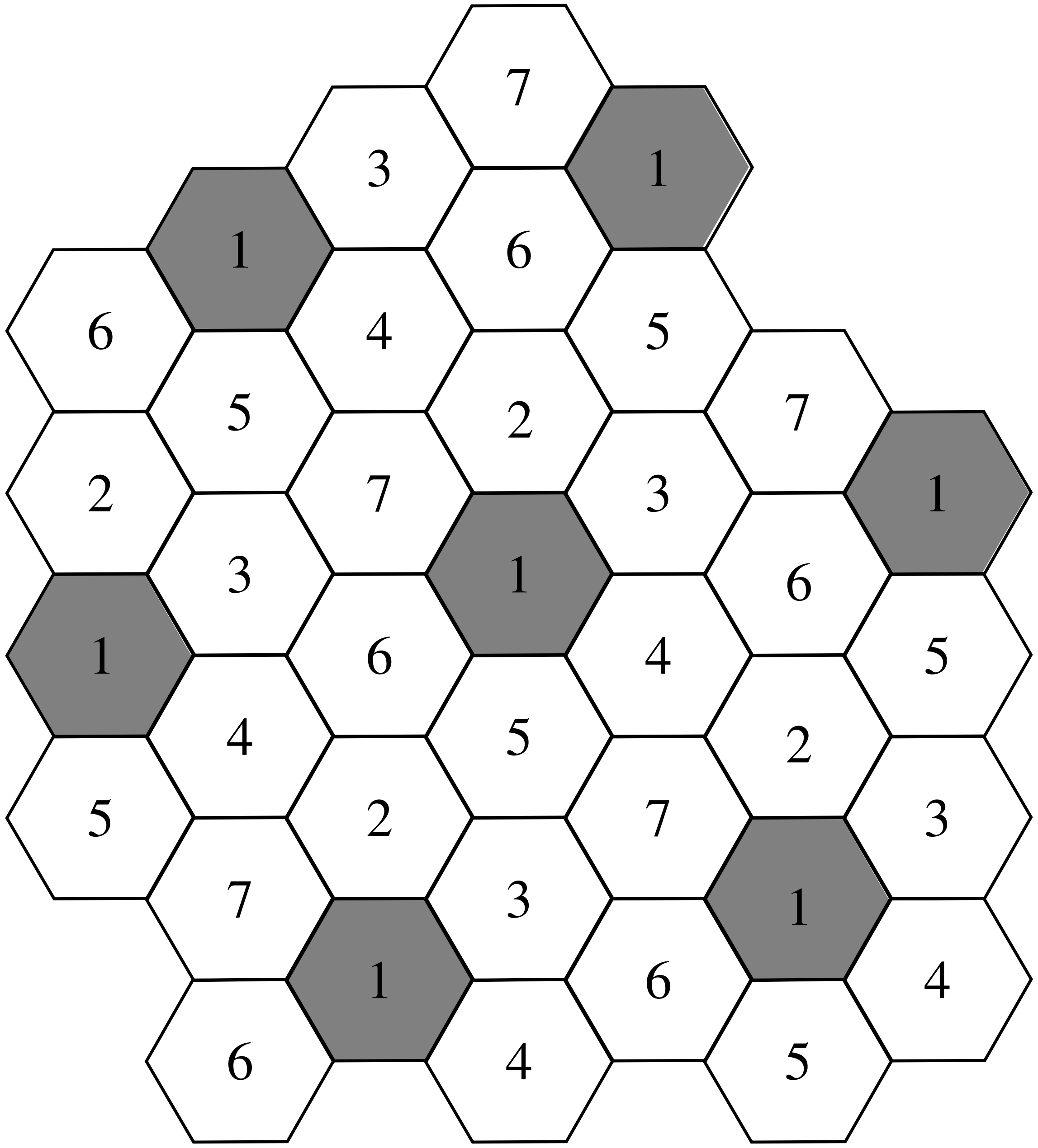
Time Division Multiple Access

GSM: 8 users share a 200 kHz sub-channel, time slot: 577 µs

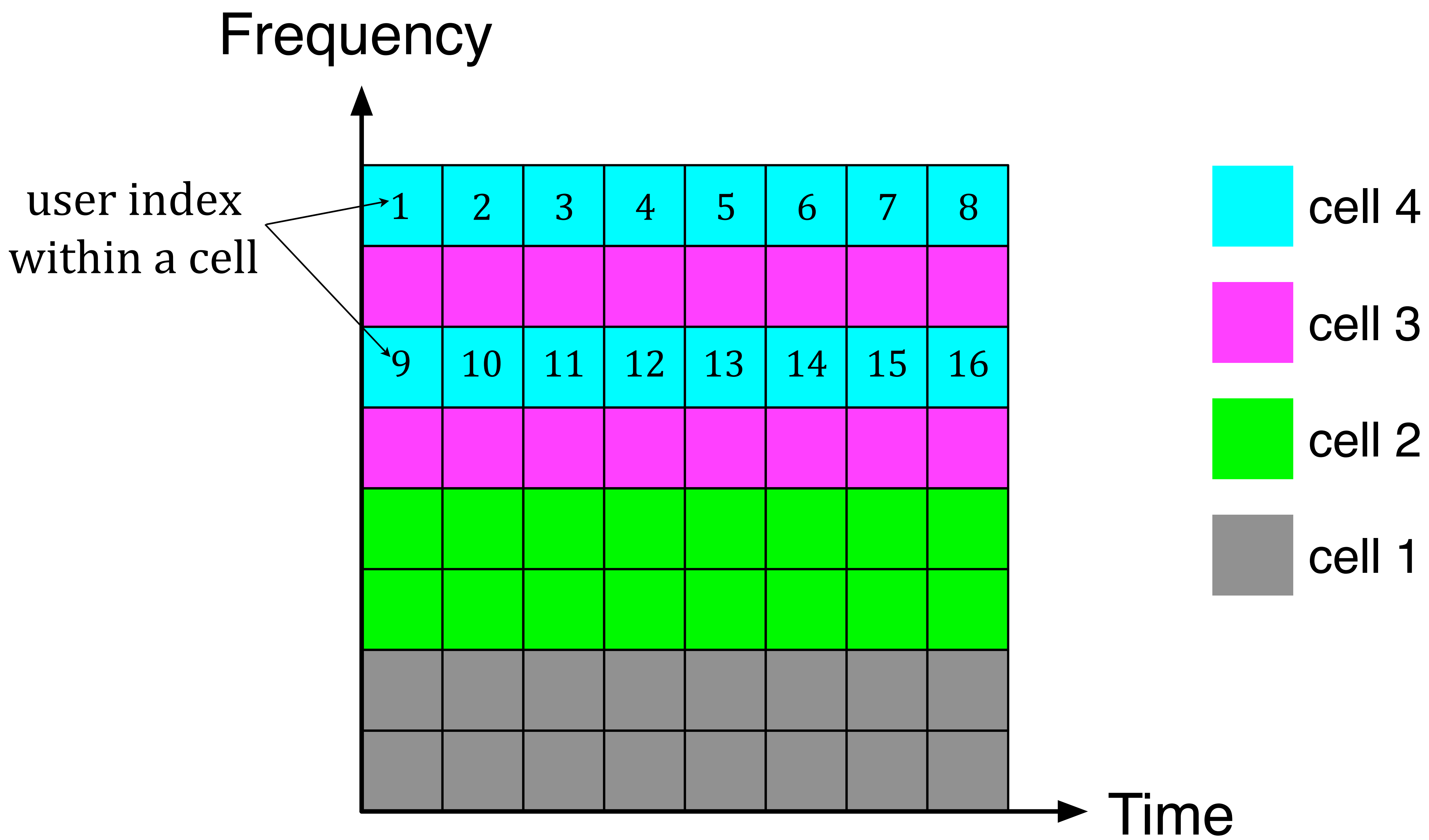


Partial Frequency Reuse

- Neighboring cells uses disjoint sets of sub-channels
- Each cell gets only 1/7 of the total bandwidth
- Frequency reuse factor = 1/7
- High SINR, but price to pay:
  - Reducing the available degrees of freedom
  - Higher complexity in network planning in real world



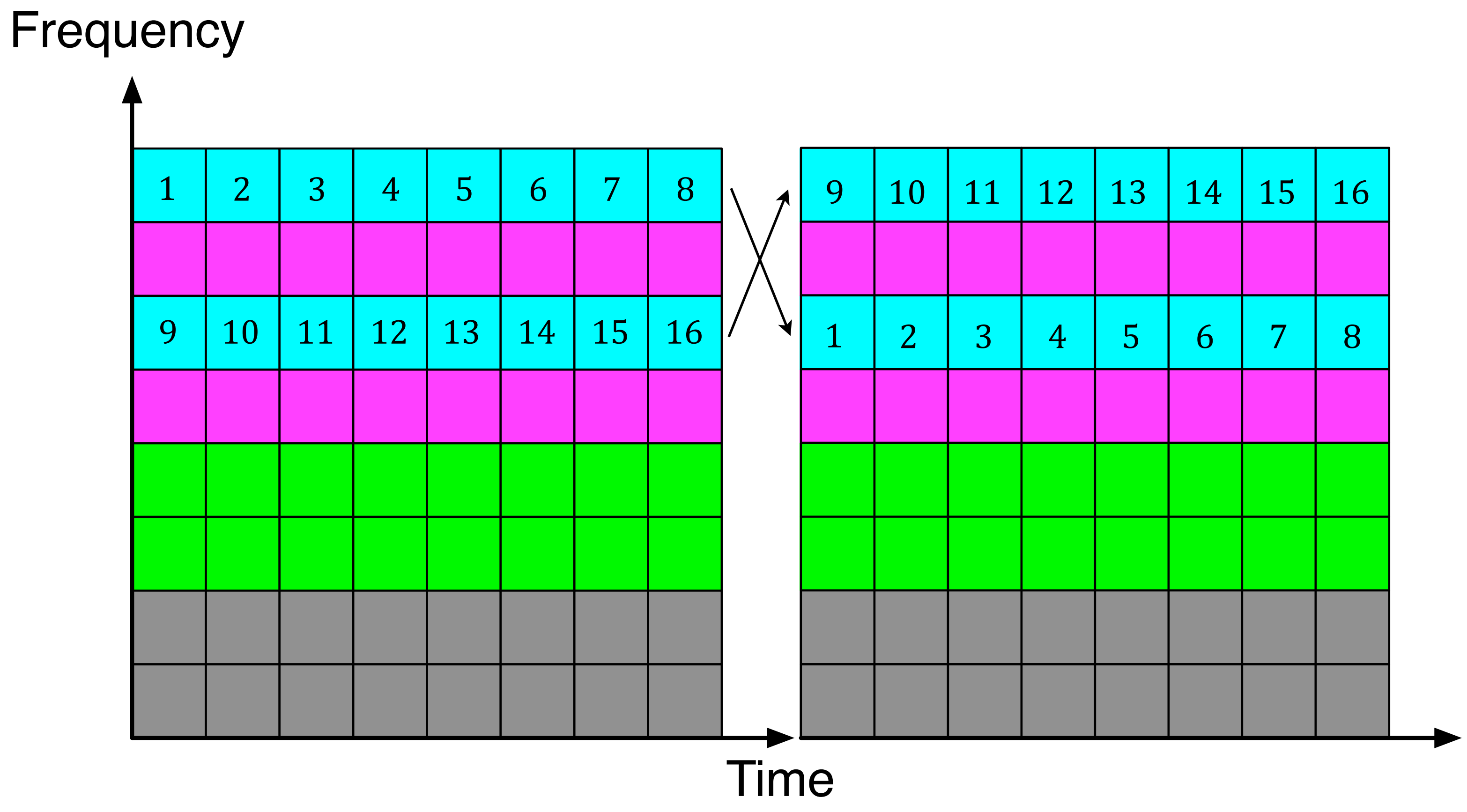
Time-Frequency Resource Allocation



Time and Frequency Diversity

- Time diversity: Coding + Interleaving

- Frequency diversity
  - Within a narrowband sub-channel: flat fading $\Longrightarrow$ no diversity
  - Obtained via frequency hopping



Why Full Frequency Reuse won't Work

- Signal-to-Interference-plus-Noise Ratio $\mathsf{SINR} = \dfrac{|h|^2 P}{N_0 + I}$
- Limiting factor: interference power I
  - I is due to the single interferer from the neighbor cell
  - I is random since the location of the single interferer is uncertain
  - Variance of I is quite large and I can be comparable with $|h|^2 P$
  - Like deep fade, but can't be handled by current diversity schemes
- Interference averaging is desired:
  - If interference come from multiple interferers with smaller power, then a similar effect in diversity schemes will emerge due to LLN!

$$I \xrightarrow{\text{becomes}} \sum_{k=1}^{N} I_k, \ \mathbb{E}[I] = \sum_{k=1}^{N} \mathbb{E}[I_k]$$

Summary

- Orthogonal narrowband channels are assigned to users within a cell

  다른 신호에 신호가 간섭하지 않는 경우.

- Users in adjacent cells can't be assigned the same channel due to lack of interference averaging across users $\Longrightarrow$ reduces the frequency reuse factor and leads to inefficient use of the total bandwidth

- The network is decomposed into a set of high SINR point-to-point links, simplifying the physical-layer design

- Frequency planning is complex, particularly when new cells have to be added

Wideband System: CDMA

Features of CDMA

code-division multiple access.

- Universal frequency reuse:
  - All users in all cells share the same bandwidth
- Main advantages:
  - Maximizes the degrees of freedom usage
  - Allows interference averaging across many users
  - Soft capacity limit (i.e., no hard limit on the # of users supported)
  - Allows soft handoff
  - Simplify frequency planning
- Challenges
  - Very tight power control to solve the near-far problem
  - More sophisticated coding/signal processing to extract the information of each user in a very low SINR environment

Design Goals

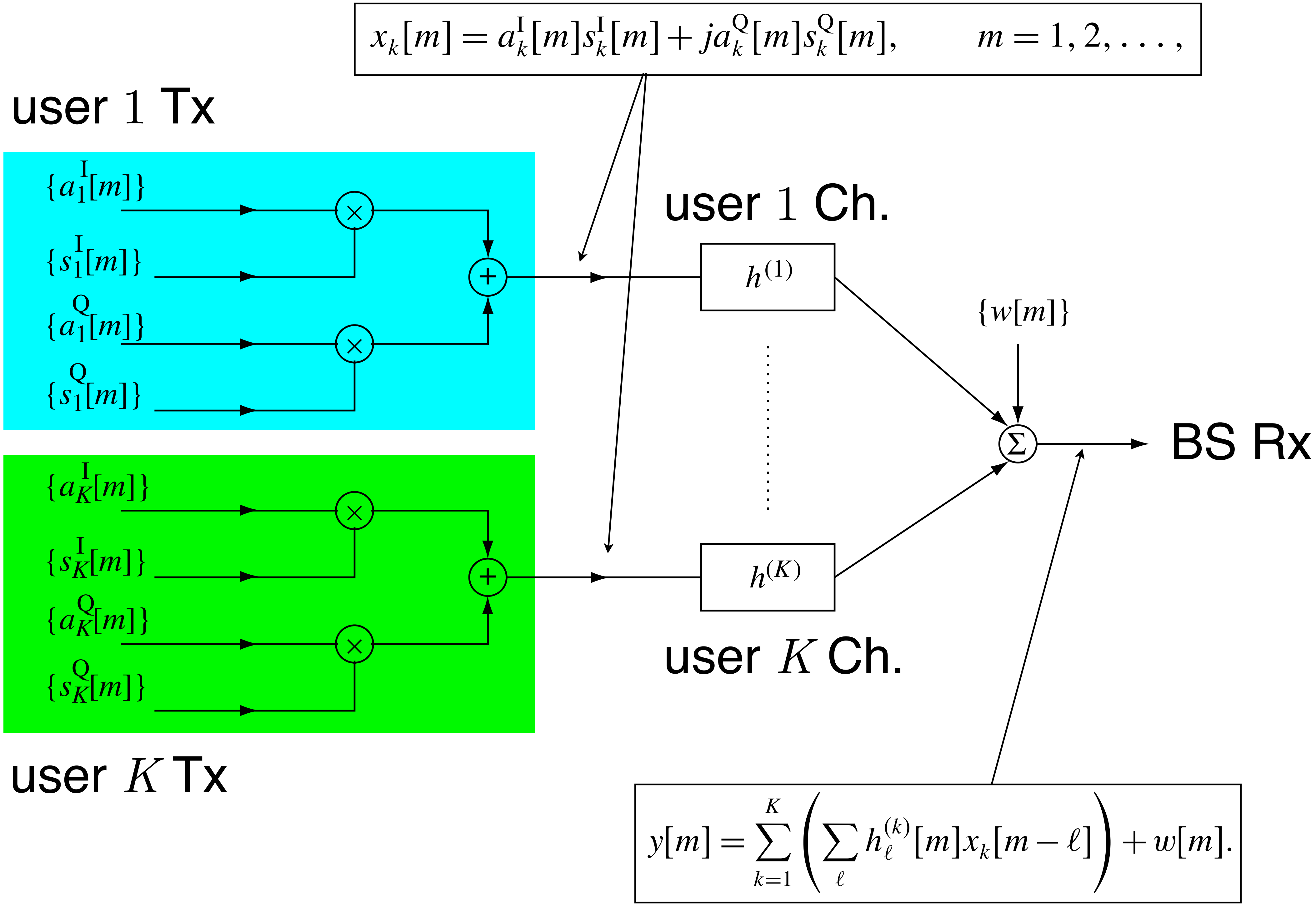
- Make the interference look as much like a white Gaussian noise as possible:
  - Spread each user's signal using a pseudonoise sequence
  - Tight power control for managing interference within the cell
  - Averaging interference from outside the cell as well as fluctuating voice activities of users

- Apply point-to-point design for each link
  - Extract all possible diversity in the channel

Point-to-Point Link Design

- Extracting maximal diversity is the name of the game
  - Because each user has an equivalent point-to-point link!
- Time diversity is obtained by interleaving across different coherence time periods and (convolutional/turbo) coding
- Frequency diversity is obtained by the Rake receiver – combining of the multipaths
- Transmit diversity is supported in 3G CDMA systems

CDMA Uplink



$x_k[m] = a_k^{\mathrm{I}}[m]s_k^{\mathrm{I}}[m] + ja_k^{\mathrm{Q}}[m]s_k^{\mathrm{Q}}[m], \qquad m = 1, 2, \ldots,$
user 1 Tx
$\{a_1^{\mathrm{I}}[m]\}$
$\{s_1^{\mathrm{I}}[m]\}$
$\{a_1^{\mathrm{Q}}[m]\}$
$\{s_1^{\mathrm{Q}}[m]\}$
$\{a_K^{\mathrm{I}}[m]\}$
$\{s_K^{\mathrm{I}}[m]\}$
$\{a_K^{\mathrm{Q}}[m]\}$
$\{s_K^{\mathrm{Q}}[m]\}$
user K Tx
user 1 Ch.
$h^{(1)}$
$h^{(K)}$
user K Ch.
$\{w[m]\}$
Σ
BS Rx
$y[m] = \sum_{k=1}^{K} \left(\sum_{\ell} h_\ell^{(k)}[m] x_k[m-\ell] \right) + w[m].$

Statistics of Interference (1/2)

- Pseudorandom sequence properties:
  - Different users use different random shift of a sequence generated by maximum length shift register (MLSR):

$$\begin{bmatrix} s[0] & s[1] & \cdots & s[G-1] \end{bmatrix}^T$$

  - I and Q channels of the same user can use the same sequence
  - Near-orthogonal property: $\sum_{m=0}^{G-1} s[m]s[m+l] = \begin{cases} G, & l = 0 \\ -1, & l \neq 0 \end{cases}$
- Effective interference for user 1: $I[m] := \sum_{k>1} \sum_{l} h_l^{(k)} x_k[m-l]$
  - Circular symmetric because each $h_l^{(k)}$ is
- Second-order statistics: approximately white

$$\mathbb{E}\left[I[m]I[m+1]^*\right] \begin{cases} = \sum_{k>1} \mathcal{E}_k^c, & l = 0 \\ \approx 0, & l \neq 0 \end{cases} \qquad \mathcal{E}_k^c := \mathbb{E}\left[|x_k[m]|^2\right] \sum_l \mathbb{E}\left[|h_l^{(k)}[m]|^2\right]$$

Statistics of Interference (2/2)

횟수 ↑ → Gaussian 분포

- Due to central limit theorem (CLT), further approximate the interference as a Gaussian random process

- Hence, the effective noise + interference for each user can be viewed as an additive white Gaussian noise!

- Remark: the assumption that each interferer contributes a roughly equal small fraction to the total interference is valid due to tight power control in CDMA

Processing Gain

- Received energy per chip:

$$\mathcal{E}_k^c := \mathbb{E}\left[|x_k[m]|^2\right] \sum_l \mathbb{E}\left[|h_l^{(k)}[m]|^2\right]$$

- SINR per chip: small

$$\mathsf{SINR}_{1,c} := \frac{\mathcal{E}_1^c}{\sum_{k \neq 1} \mathcal{E}_k^c + \sigma^2}$$

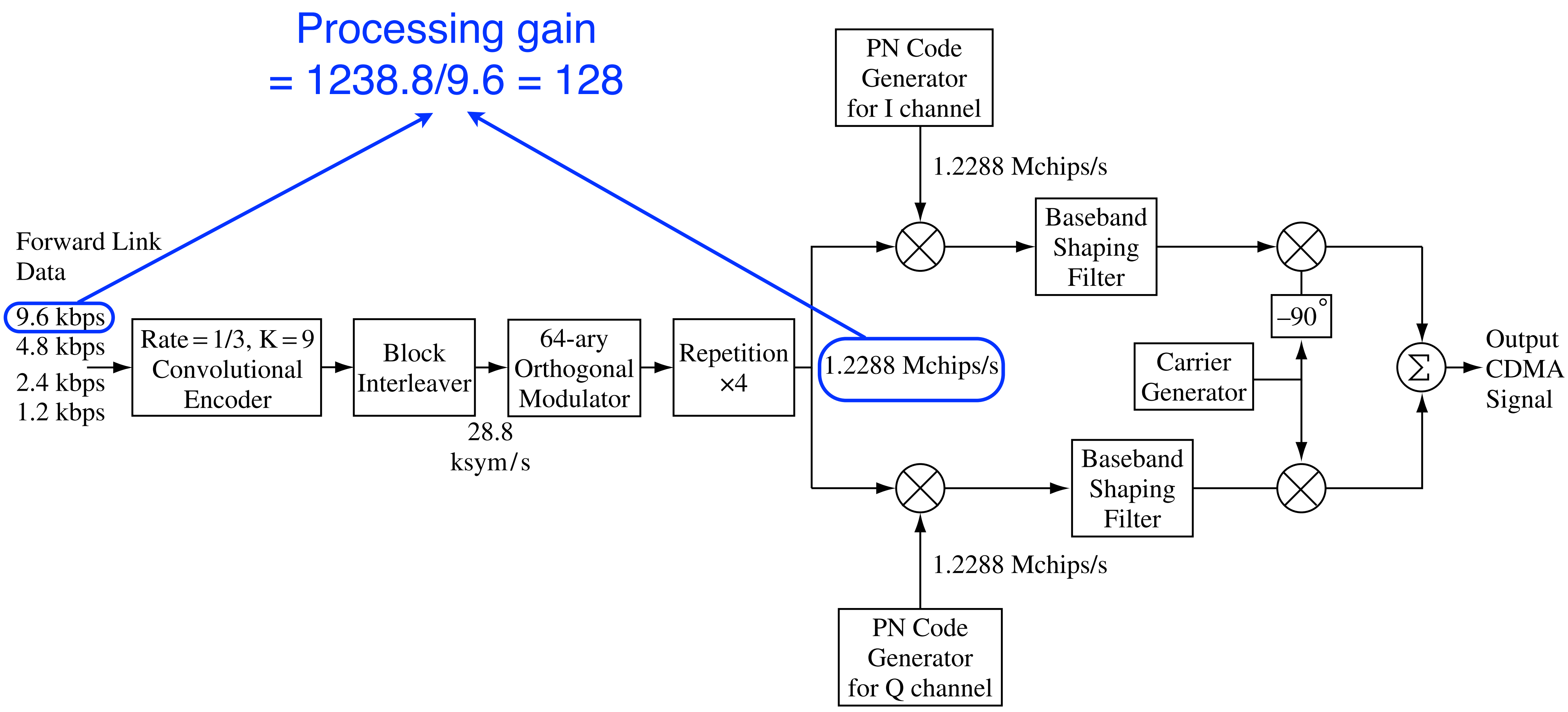
- SINR per bit:

$$\mathsf{SINR}_{1,b} := \frac{||\mathbf{u}||^2 \mathcal{E}_1^c}{\sum_{k \neq 1} \mathcal{E}_k^c + \sigma^2} = \frac{\overbrace{G\mathcal{E}_1^c}^{\mathcal{E}_1^b}}{\sum_{k \neq 1} \mathcal{E}_k^c + \sigma^2}$$

$$\mathbf{u} = \begin{bmatrix} s_1^I[0] & s_1^I[1] & \cdots & s_1^I[G-1] \end{bmatrix}^T$$

- G: Processing Gain

IS-95 Uplink Architecture



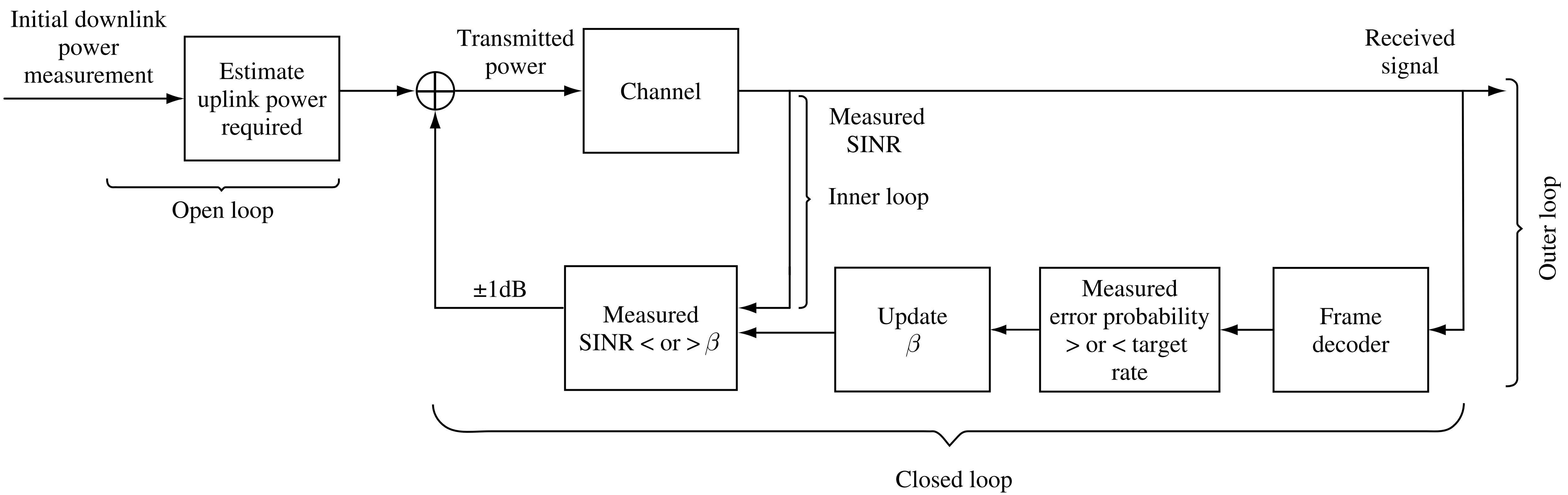
Power Control

- Maintain equal received power for all users in the cell
- Tough problem since the dynamic range is very wide. Users' attenuation can differ by many 10's of dB

- Consists of both open-loop and closed loop
  - Open loop sets a reference point
  - Closed loop is needed since IS-95 is FDD
- Consists of 1-bit up-down feedback at 800 Hz

- Consumes about 10% of capacity in IS-95
- Latency in access due to slow powering up of mobiles

Power Control Architecture



Interferene Averaging

- The received SINR for a user:

$$\mathsf{SINR} = \frac{P}{N_0 + (K-1)P + \sum_{i \notin \text{cell}} I_i}$$

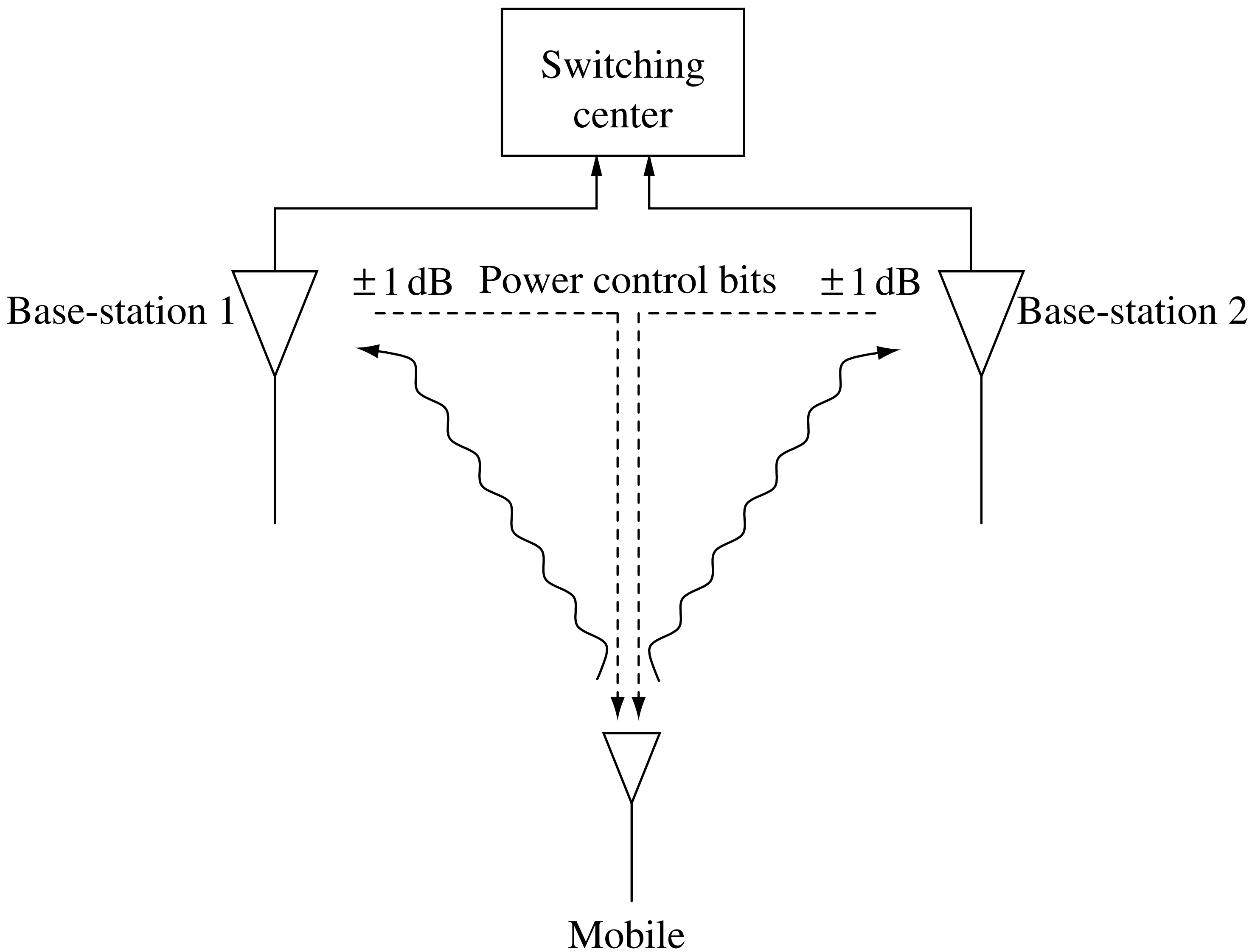
- In a large system, each interferer contributes a small fraction of the total out-of-cell interference
  - Made possible due to power control

- This can be viewed as providing interference diversity

- Same interference-averaging principle applies to voice bursty activity and imperfect power control

Soft Handoff

- Provides another form of diversity: macrodiversity
  - Two base stations can simultaneously decode the data



Uplink vs. Downlink

- Near-far problem does not exist in DL $\Longrightarrow$ power control is less crucial
- Tx can make DL signals for different users orthogonal
  - Still, due to multipaths, not completely orthogonal at the receiver
- Rake is highly sub-optimal in the downlink
  - Equalization is beneficial as all users' data go through the same channel and the aggregate rate is high
- Less interference averaging in the downlink
  - Interference comes from a few high-power base stations as opposed to many low-power mobiles

Issues with CDMA

- In-cell interference reduces capacity = data rate
  초당 보낼수 있는 data

- Power control is expensive, particularly for data applications where users have low duty cycle but require quick access to resource

- In-cell interference is not an inherent property of systems with universal frequency reuse

  $\Longrightarrow$ We can keep users in the cell orthogonal, and still have universal frequency reuse

Wideband System: OFDMA

Basic Ideas

- Lecture 2: OFDM as a point-to-point modulation scheme, converting an ISI channel into parallel channels

- It can also be used as a multiple access technique!
  - By assigning different time/frequency slots to users, they can be kept orthogonal within a cell
  - Equalization is no longer needed

- How to deal with inter-cell interference?

  $\Longrightarrow$ Interference averaging

  Achieved by careful design of hopping matrices (a way of subcarrier allocation)

Hopping Sequences as Virtual Channels

- Basic unit of resource: a virtual channel
  – Hopping sequence over time-frequency plane

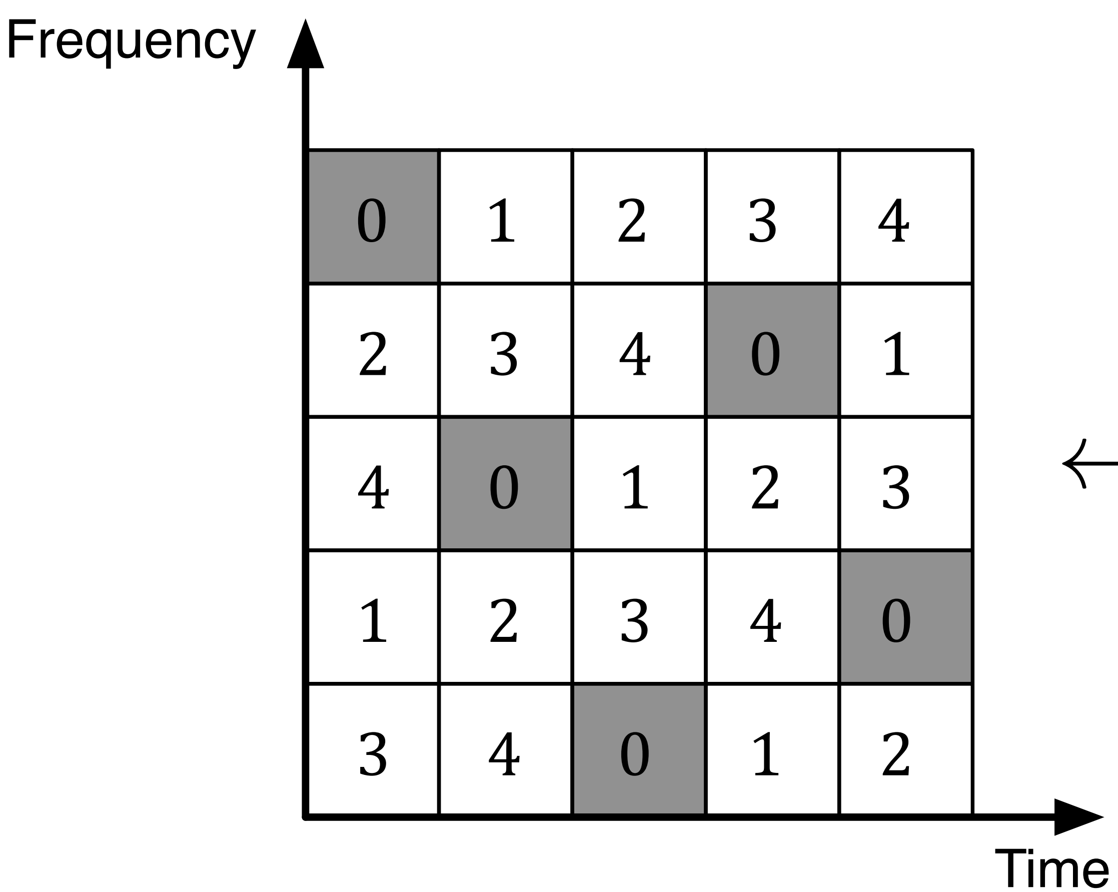
- Coding across the symbols in a hopping sequence
  - If there were no coding and coding across subcarriers, the OFDM system would behave like narrowband systems due to lack of interference averaging!

- Hopping sequences are orthogonal within a cell
- Each user is assigned a number of virtual channels depending on their data rate requirement

Design Principles

- Spread out the subcarriers for one user to gain frequency diversity
- Hop the subcarrier allocation every OFDM block

$N_c = 5$, and 5 users



$\longleftrightarrow$

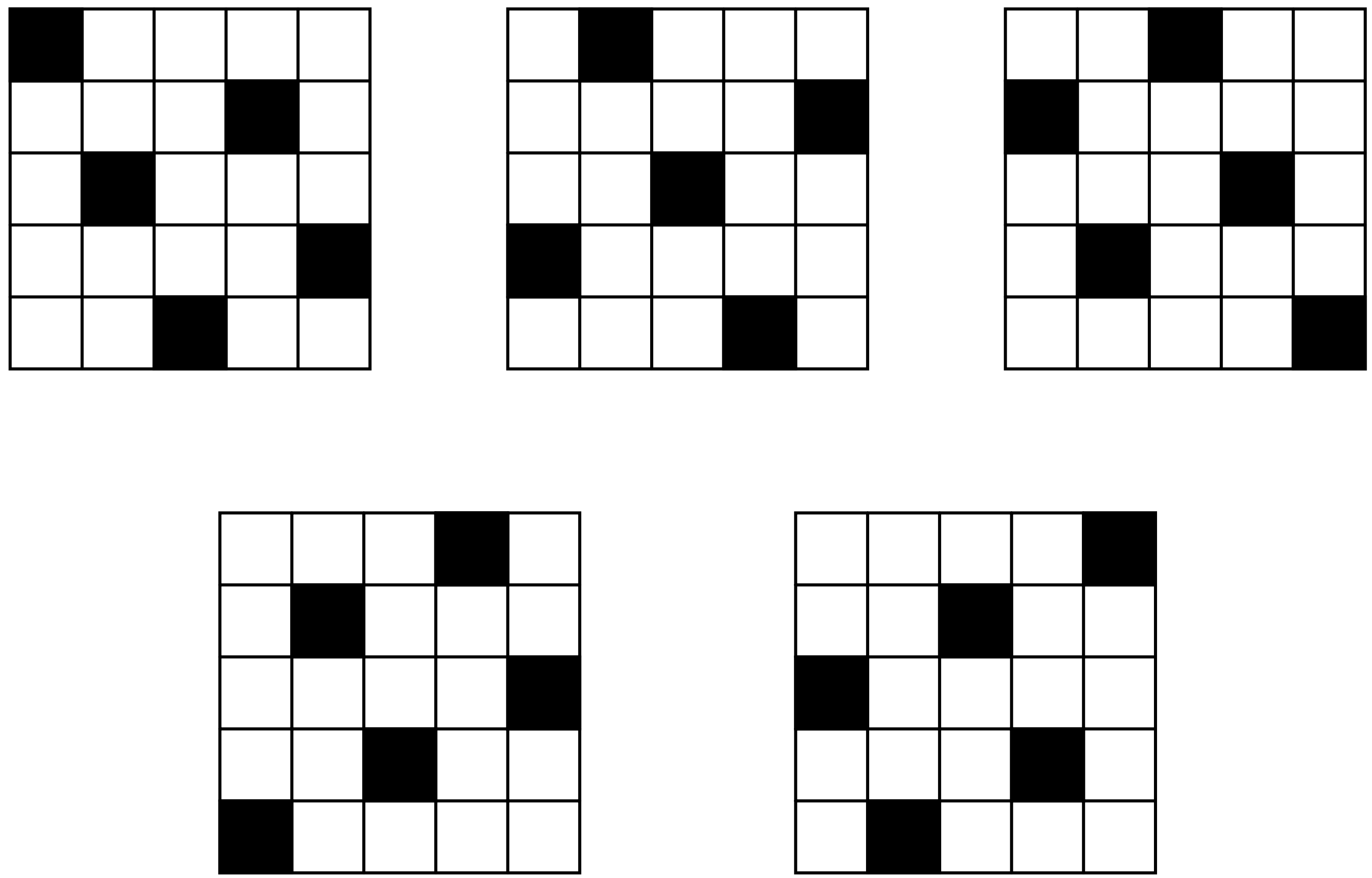
Hopping Matrix
(Latin square)

$$\begin{bmatrix} 0 & 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 0 & 1 \\ 4 & 0 & 1 & 2 & 3 \\ 1 & 2 & 3 & 4 & 0 \\ 3 & 4 & 0 & 1 & 2 \end{bmatrix}$$

Each row/column is a permutation of $[0{:}N_c{-}1]$

Hopping Sequences

Virtual Channel 0 Virtual Channel 1 Virtual Channel 2



Virtual Channel 3 Virtual Channel 4

Hopping Matrix Design

- Each base station has its own hopping matrix
- Design rule: maximize the number of interferers that one user encountered $\Longrightarrow$ min. overlap of hopping matrices
  - Latin squares with this property are called orthogonal

Bad Choice

Cell A

$$\begin{bmatrix} \boxed{0} & 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & \boxed{0} & 1 \\ 4 & \boxed{0} & 1 & 2 & 3 \\ 1 & 2 & 3 & 4 & \boxed{0} \\ 3 & 4 & \boxed{0} & 1 & 2 \end{bmatrix}$$

Cell B

$$\begin{bmatrix} \boxed{0} & 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & \boxed{0} & 1 \\ 4 & \boxed{0} & 1 & 2 & 3 \\ 1 & 2 & 3 & 4 & \boxed{0} \\ 3 & 4 & \boxed{0} & 1 & 2 \end{bmatrix}$$

user 0 in cell A always interferes with user 0 in cell B!

Good Choice

Cell A

$$\begin{bmatrix} \boxed{0} & 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & \boxed{0} & 1 \\ 4 & \boxed{0} & 1 & 2 & 3 \\ 1 & 2 & 3 & 4 & \boxed{0} \\ 3 & 4 & \boxed{0} & 1 & 2 \end{bmatrix}$$

Cell B

$$\begin{bmatrix} \boxed{0} & 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & \boxed{4} & 0 \\ 2 & \boxed{3} & 4 & 0 & 1 \\ 3 & 4 & 0 & 1 & \boxed{2} \\ 4 & 0 & \boxed{1} & 2 & 3 \end{bmatrix}$$

user 0 in cell A interferes with user 0, 3, 1, 4, 2 in cell B respectively

Mutually Orthogonal Latin Squares

- For a prime N_c, a simple construction of a family of N_c–1 mutually orthogonal Latin squares are as follows:

  For $a \in \{1, 2, \ldots, N_c - 1\}$, define an $N_c \times N_c$ matrix $\mathbf{R}^a$
  with (i, j)-th enrty $R^a_{ij} = ai + j \mod N_c$,
  where $i, j \in \{0, 1, \ldots N_c - 1\}$

- It can be shown that $a \neq b \Longrightarrow \mathbf{R}^a$ and $\mathbf{R}^b$ are orthogonal

Out-of-Cell Interference Averaging

- The hopping patterns of virtual channels in adjacent cells are designed such that any pair has minimal overlap
- This ensures that a virtual channel sees interference from many users instead of a single strong user
- This is a form of interference diversity

Example: Flash OFDM

- Bandwidth = 1.25 Mz
- # of data sub-carriers = 113
- OFDM symbol = 128 samples = 100 μ s
- Cyclic prefix = 16 samples = 11 μ s delay spread

- OFDM symbol time determines accuracy requirement of user synchronization (not chip time, better than CDMA)

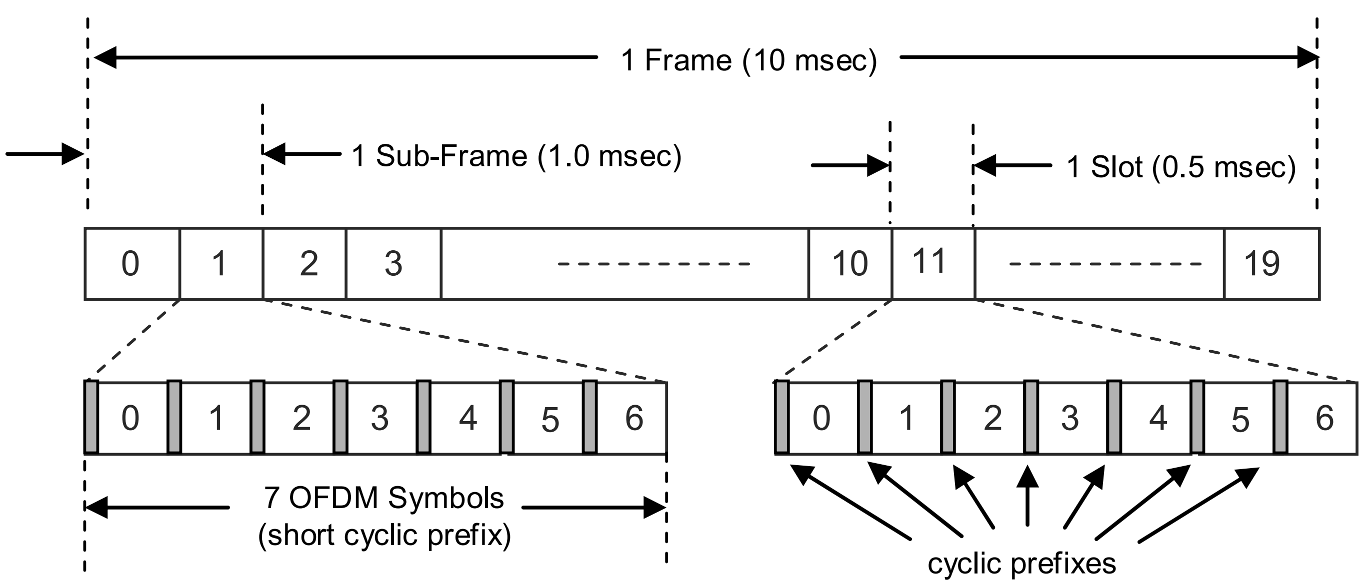
- Ratio of cyclic prefix to OFDM symbol time determines overhead (fixed, unlike power control in CDMA)

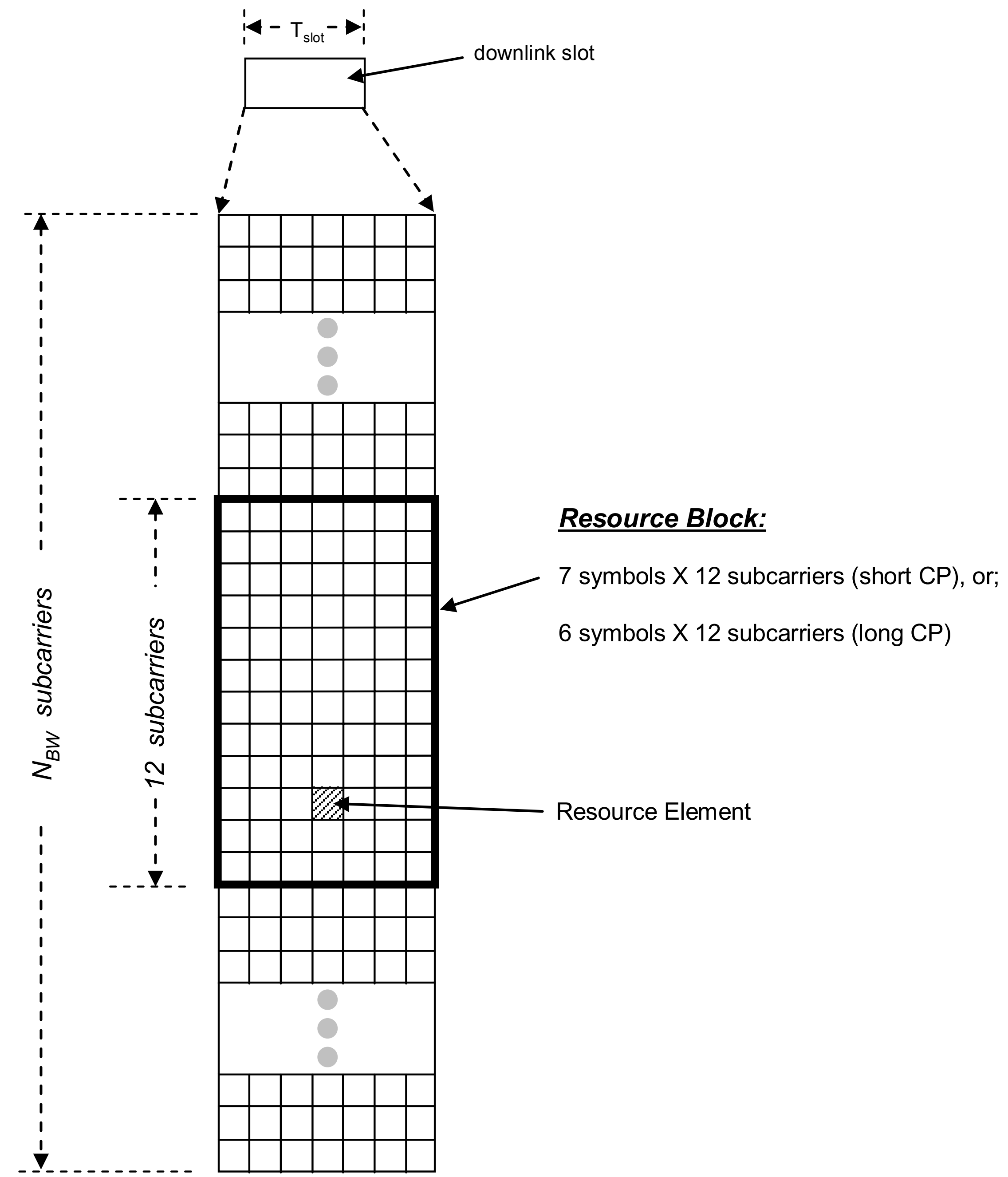
States of Users

- Users are divided into 3 states:
  - Active: users that are currently assigned virtual channels (<30)
  - Hold: users that are not sending data but maintain synchronization (<130)
  - Inactive (<1000)
- Users in hold state can be moved into active state very quickly
- Because of the orthogonality property, tight power control is not crucial and this enables quick access for users
  - Important for certain applications (requests for http transfers, acknowledgements, etc.)

OFDMA in LTE

- In LTE, OFDMA is used in downlink
  - Basic unit of resource is a 12 sub-carrier × 7 OFDM symbol time block

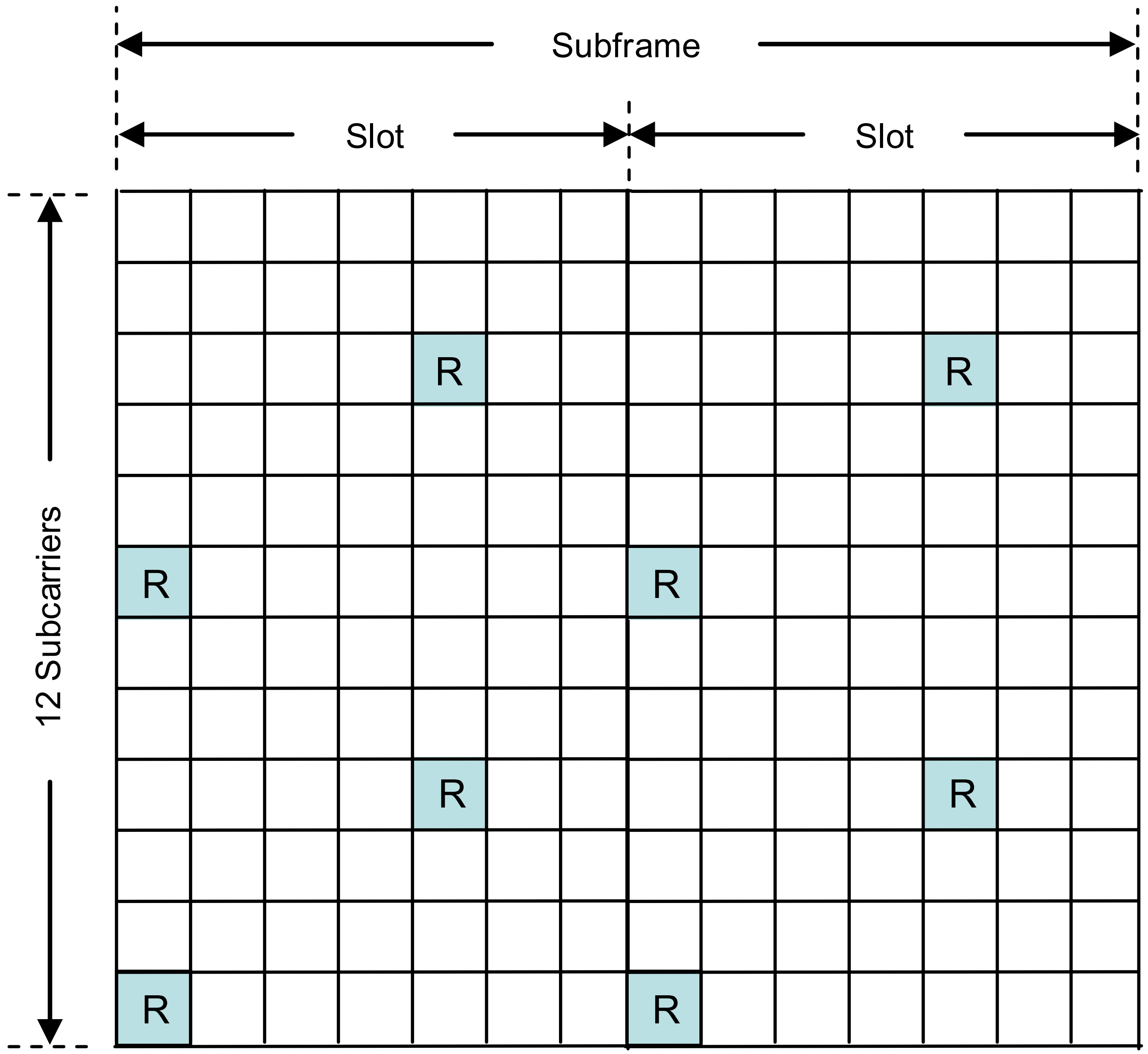




  - Interference averaging is achieved by hopping over different blocks over time
  - Less averaging than symbol-by-symbol hopping but facilitate channel estimation

Channel Estimation

- Channel estimation is achieved by interpolating between the pilots



Peak-to-Average Power Ratio

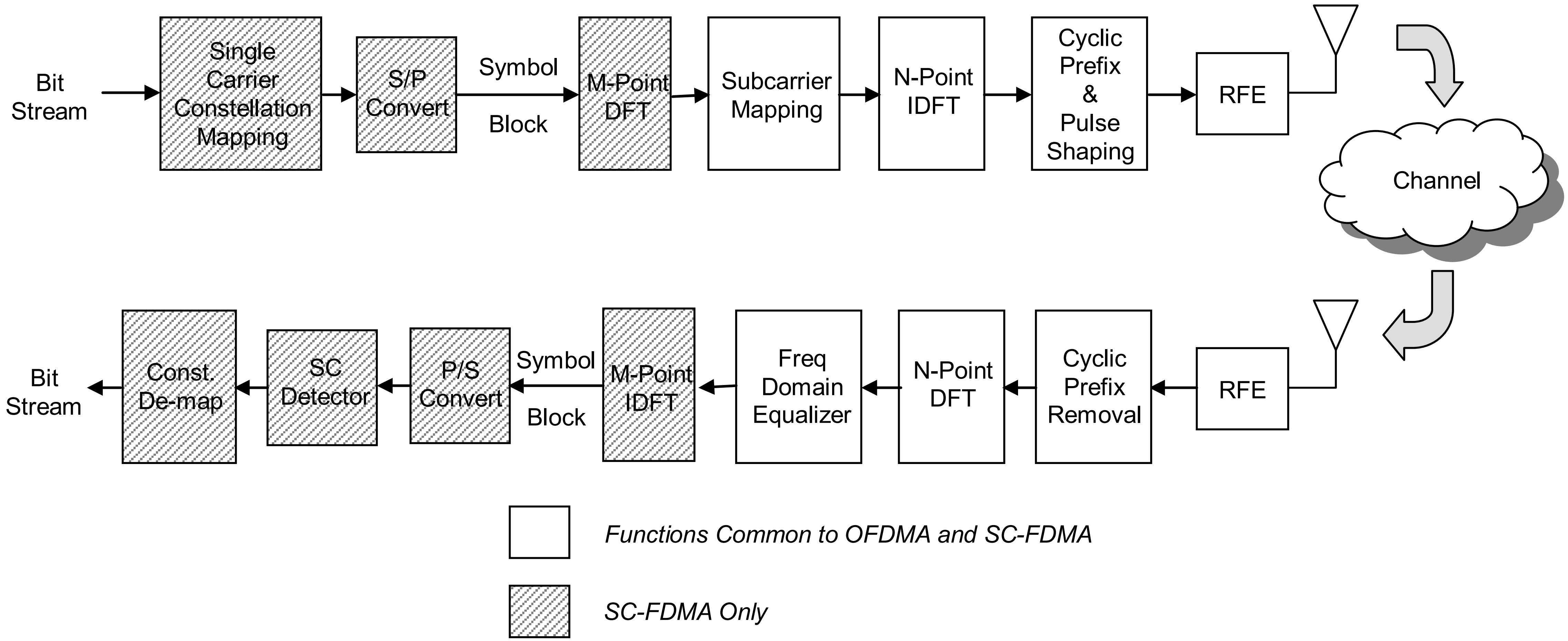
최대전력-평균전력 비

- OFDM transmitted signal has a high PAPR due to superposition of many independent sub-carrier symbols

- This leads to significant backoff in the power amplifier setting and low efficiency
- Particularly significant issue in the uplink

- Several engineering solutions to this problem
- Current version of LTE uplink uses OFDM for multiple access but single carrier transmission per user.

LTE Uplink: SC-FDMA



Summary

	Narrowband system	Wideband CDMA	Wideband OFDMA
Signal	Narrowband	Wideband	Wideband
Intra-cell bandwidth allocation	Orthogonal	Pseudorandom	Orthogonal
Intra-cell interference	None	Significant	None
Inter-cell bandwidth allocation	Partial reuse	Universal reuse	Universal reuse
Inter-cell uplink interference	Bursty	Averaged	Averaged
Accuracy of power control	Low	High	Low
Operating SINR	High	Low	Range: low to high
PAPR of uplink signal	Low	Medium	High