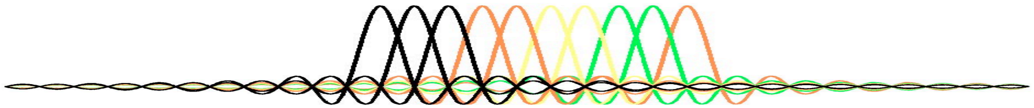


EHB 453, Introduction to Mobile Communications

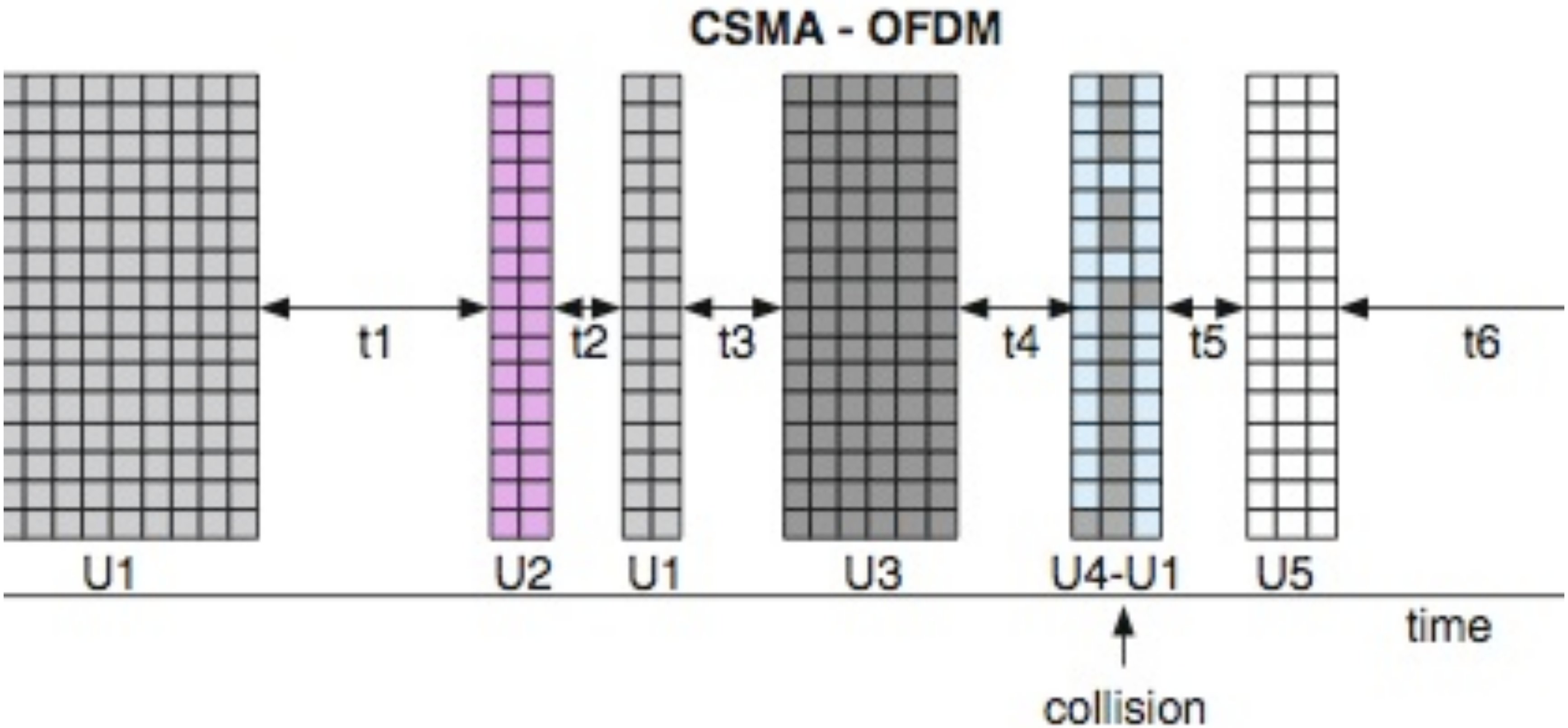
Lecture 5: OFDMA and MIMO

Prof. Mustafa Ergen

Outline

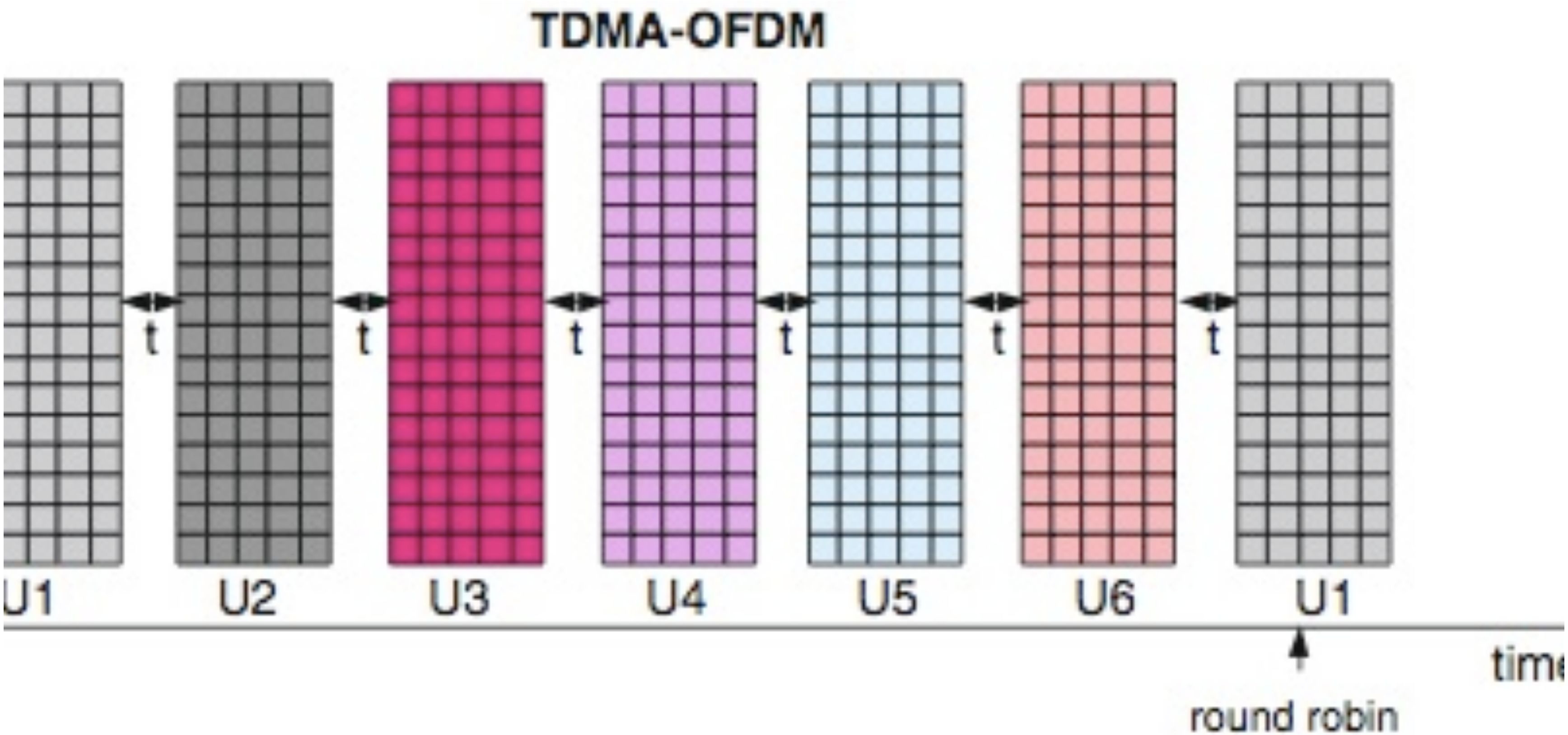
- What is OFDMA?
- Resource Allocation
- Single Frequency Network
- Flash - OFDM

CSMA-OFDM



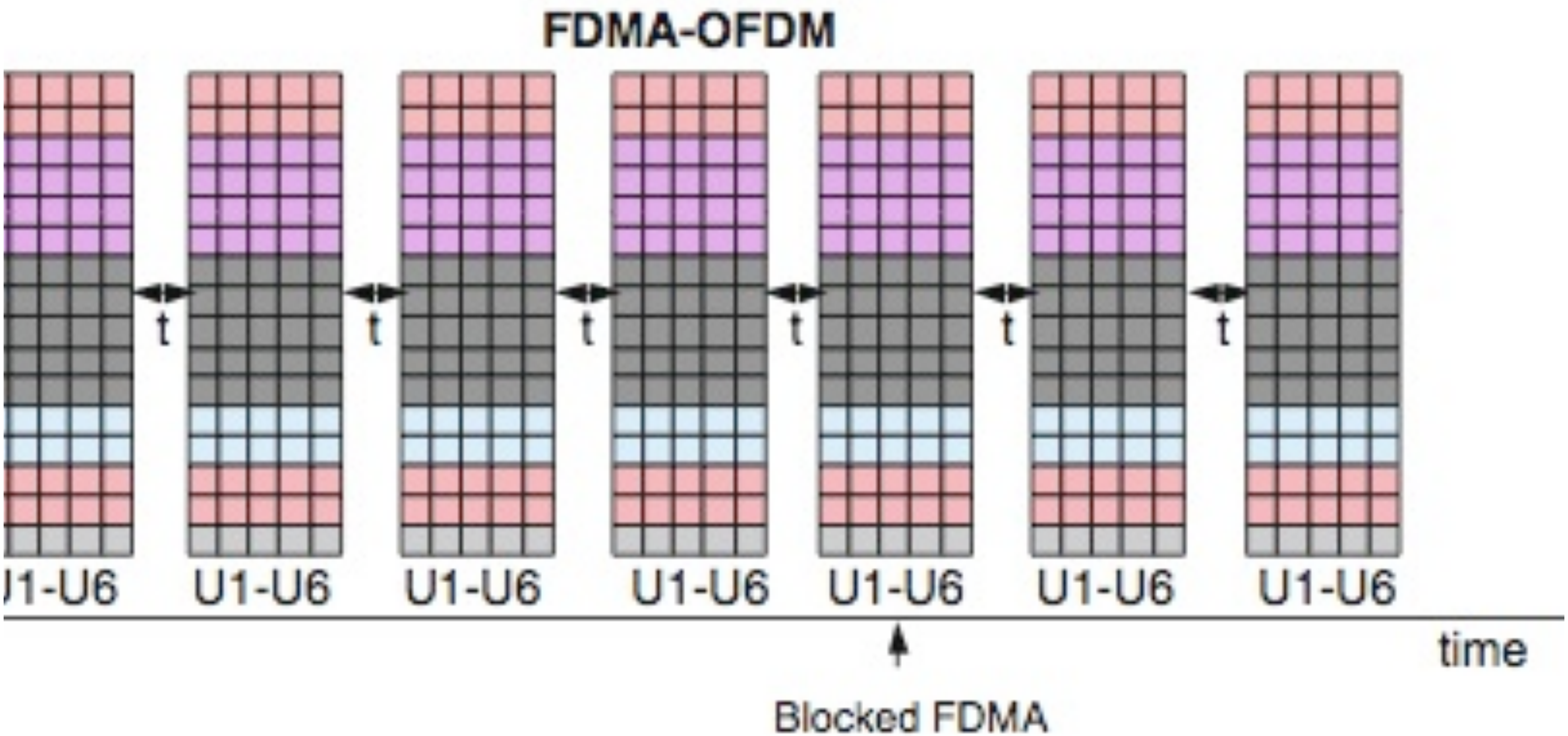
IA-OFDM: There are 6 users (U), and CSMA scheme has random
es (ti) and random packet sizes

TDMA-OFDM



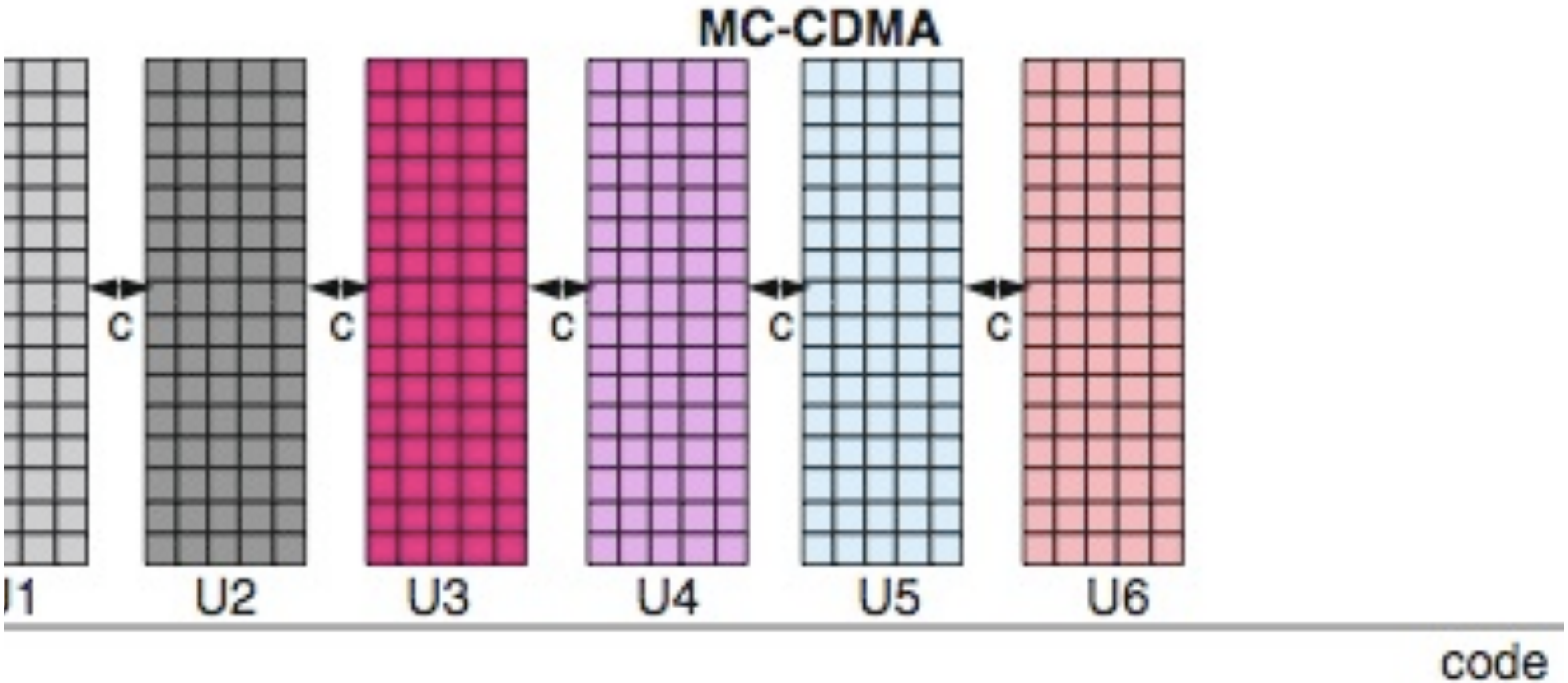
A-OFDM: There are 6 users (U), and TDMA scheme has fixed ti
) and fixed packet sizes

FDMA-OFDM



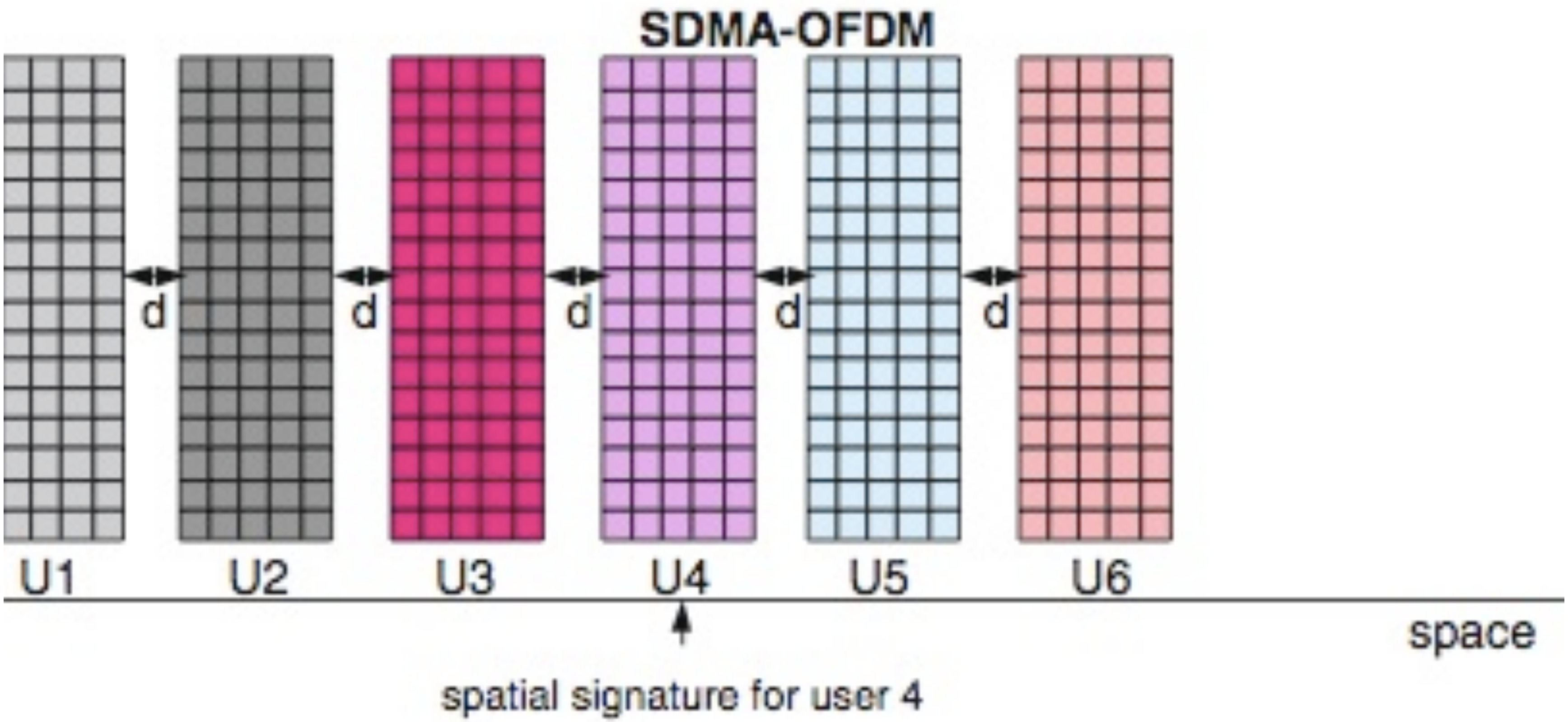
A-OFDM: There are 6 users (U), and Block-FDMA scheme has fixe
s (t) and fixed subcarrier allocation

MC-OFDM



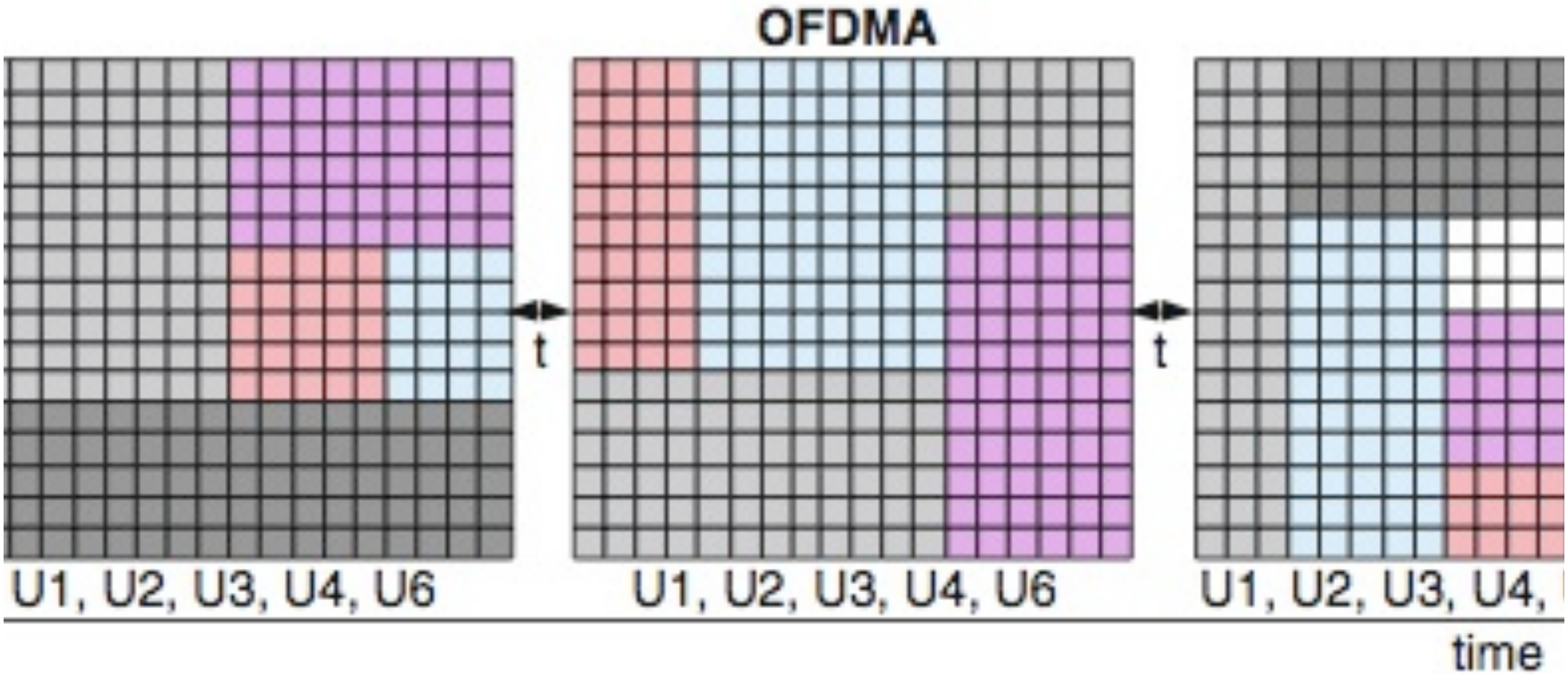
)MA: There are six users (U), and time-spread MC-CDMA sche
:) for orthogonality

SDMA-OFDM



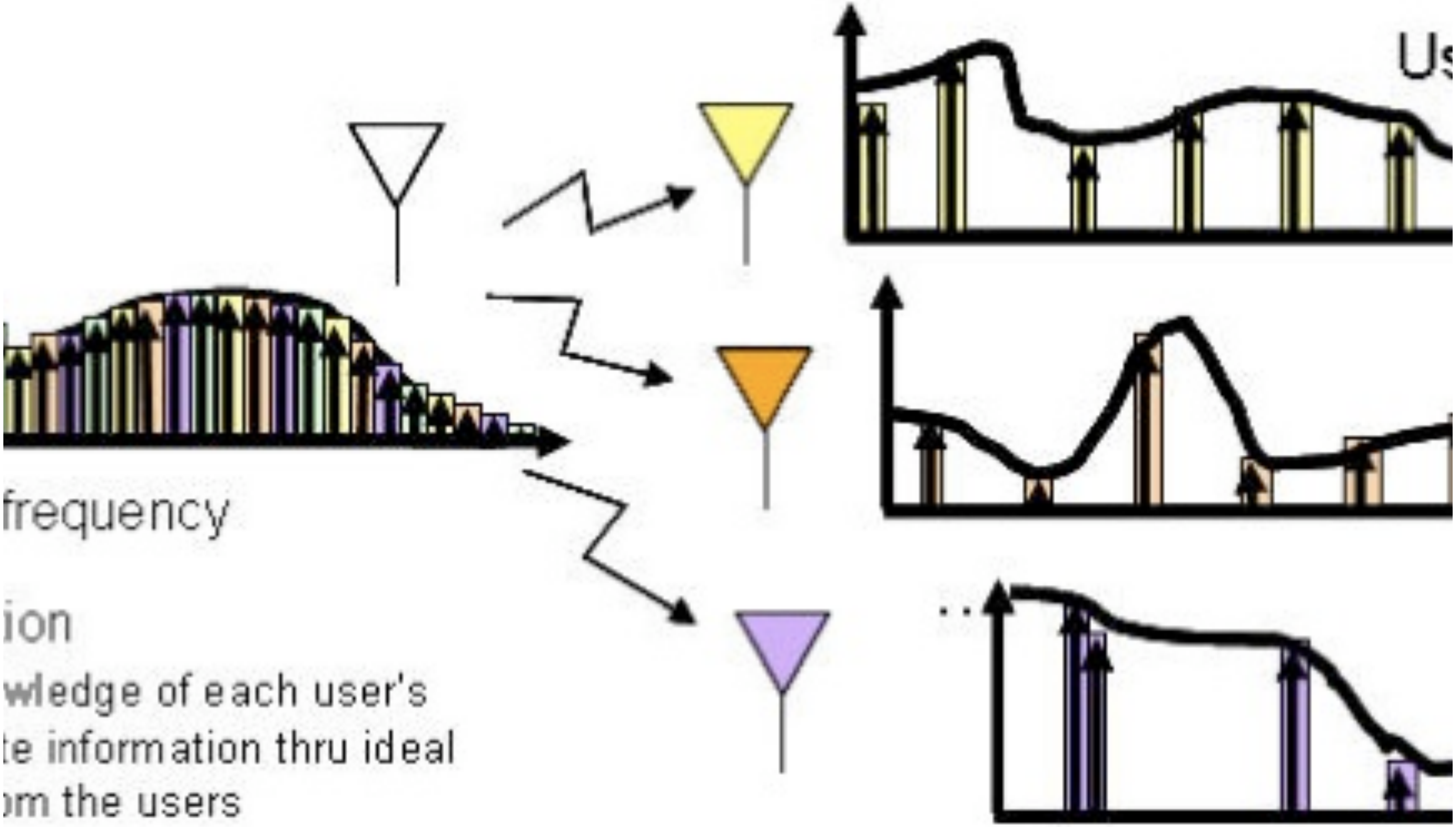
A-OFDM: There are 6 users (U), and SDMA scheme has physical di
r orthogonality

OFDMA



A: There are 6 users (U), and OFDMA scheme has fixed distance lot and subcarrier allocation

OFDMA


Us
frequency
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wledge of each user's
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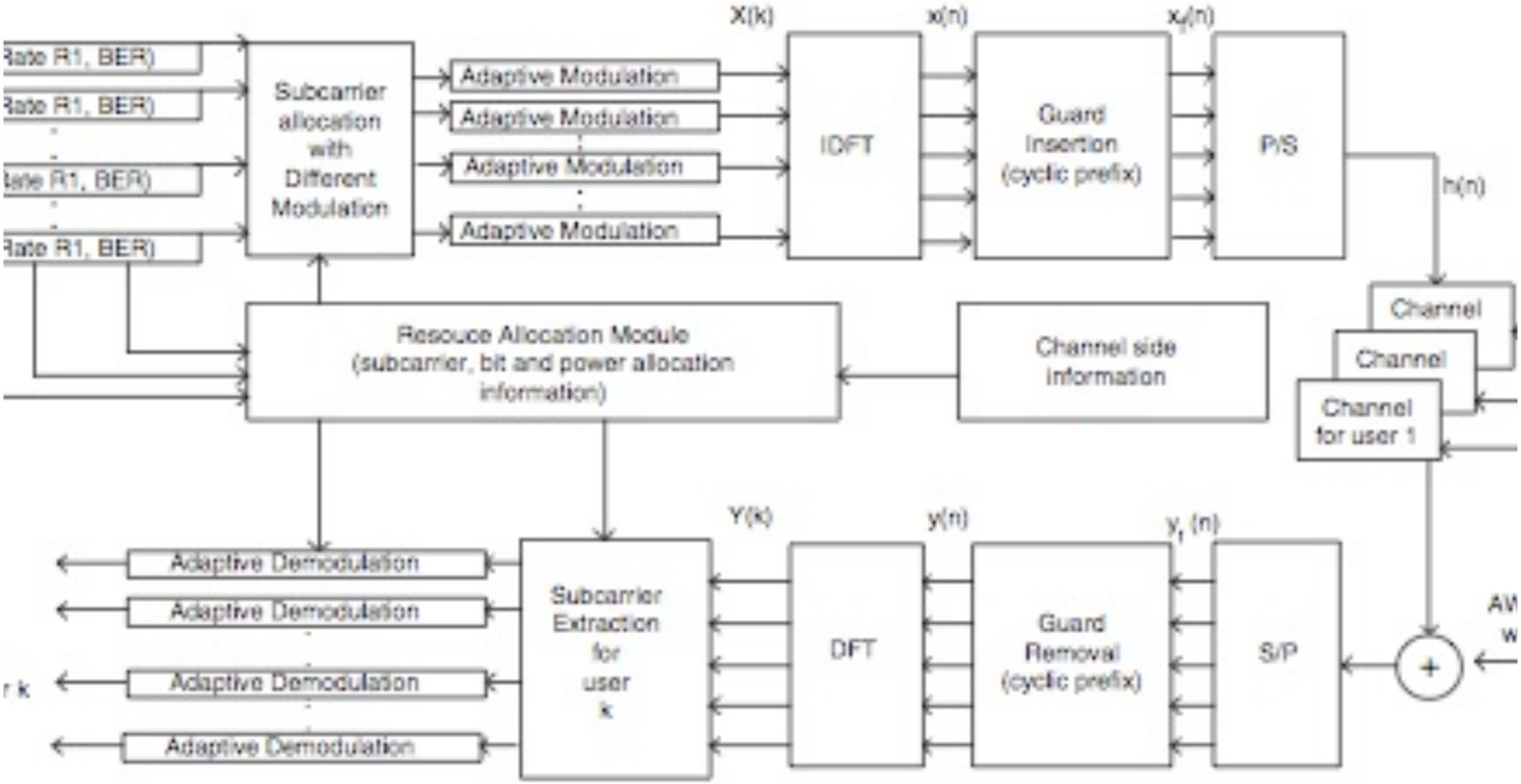
om the users

Drawbacks

- Power inefficient compared to OFDM
- OFDMA electronics, including FFTs and Forward Error Correction (FEC) is complex.
- Frequency-selective fading and diversity gain benefits could be at least partly lost if very few sub-carriers are assigned to each user, and if the same carrier is used in every OFDM symbol.
- Dealing with co-channel interference from nearby cells is more complex in OFDM than in CDMA.

Source: http://www.wirelessnetdesignline.com/howto/broadband/198000601;jsessionid=CZFRNRNKHXQGBQE1GHPCKHWATMY32JVN?pgno=2

Scalable OFDM



ogonal frequency division multiple access system

Scalable OFDMA

between 2–6 GHz, considers mobility at a maximum speed of 125 km/h (35 m/s). Doppler shift for operation in 2.5 GHz carrier frequency (f_c) is

$$f_m = \frac{v f_c}{c} = \frac{35\,m/s\,2.5 10^9\,Hz}{3x10^8\,m/s} = 291\,Hz \tag{5.1}$$

and it is 408 Hz when $f_c = 3.5$ GHz and 700 Hz when $f_c = 6$ GHz. When maximum Doppler shift is considered, coherence time of the channel is $T_C = \sqrt{\frac{9}{16.\pi.f_m^2}} = 1.1$ ms. This would require an update rate of ≈1KHz for channel estimation and equalization. The delay spread (T_S) for mobile environment is 20 μs specified by The International Telecommunications Union (ITU-R).[2] Associated coherence bandwidth (B_C) is

$$B_C \approx \frac{1}{5.T_S} = \frac{1}{5.20\,\mu s} = 10\,KHz, \tag{5.2}$$

where sought frequency correlation is 50%. This means that over a 10-KHz subcarrier width, the fading is considered flat.

SOFDMA subcarrier spacing is independent of channel bandwidth. Scalability ensures that system performance is consistent across different RF channel sizes

Subcarrier Allocation: Fixed QoS Constraints

- With the channel information, the objective of resource allocation problem can be defined as maximizing the throughput subject to a given total power constraint regarding the user's QoS requirements.

C is bits per symbol

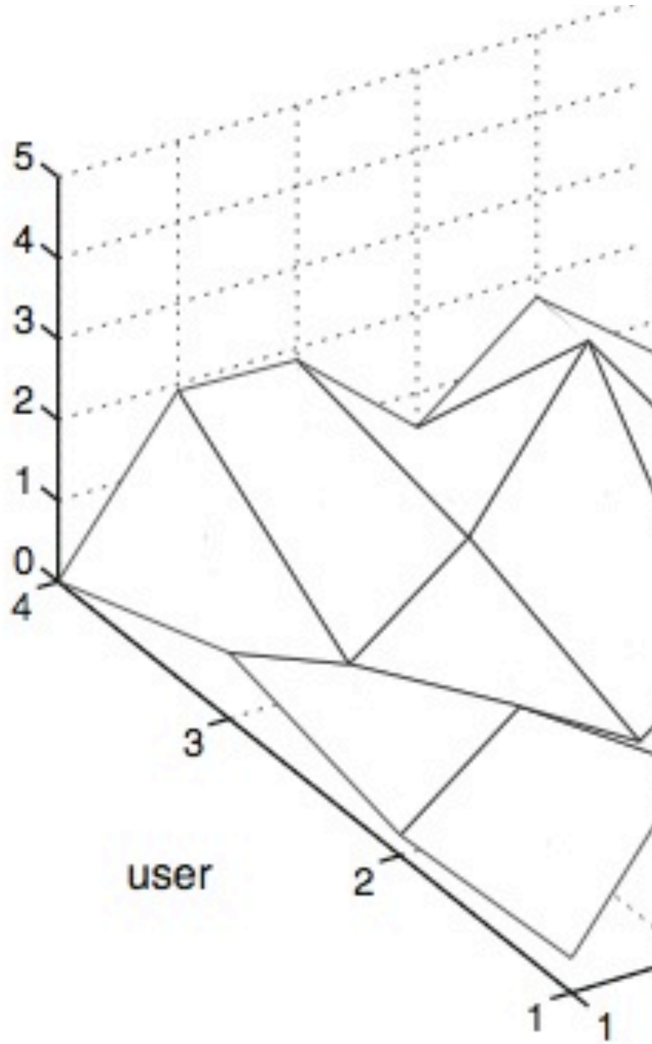
Indicator: 1 if that subcarrier is allocated

$$\max_{c_{k,n},\gamma_{k,n}} R_k = \sum_{n=1}^{N} c_{k,n}\gamma_{k,n} \quad \text{for all k}$$

$$\text{subject to } P_T = \sum_{k=1}^{K}\sum_{n=1}^{N} \frac{f_k(c_{k,n},\text{BER}_k)}{\alpha_{k,n}^2}\gamma_{k,n} \le P_{\max},$$

Power allocated to the nth user

Subcarrier Allocation: Fixed QoS



User	1	2	3	4
Rate (bits)	12	6	6	8
BER	1e-2	1e-2	1e-4	1e-4

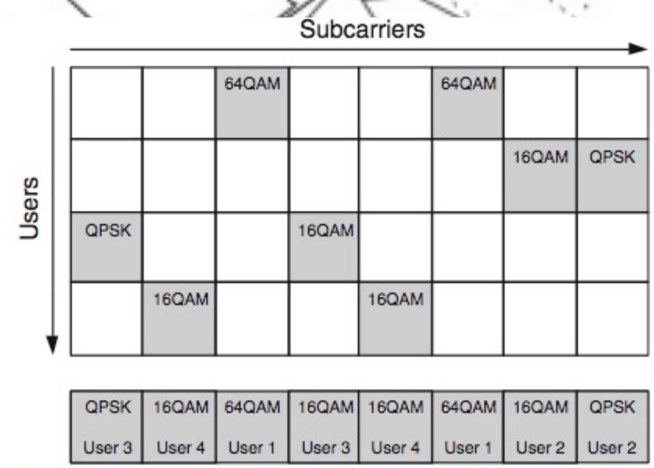


Fig. 5.9 Optimal resource allocation and bit loading

Subcarrier Allocation: Variable QoS

- Another way to approach resource allocation is in terms of capacity. Suppose there is no fixed requirements per symbol and the aim is to maximize capacity.

subcarrier

Data requirement divided by number of subcarriers

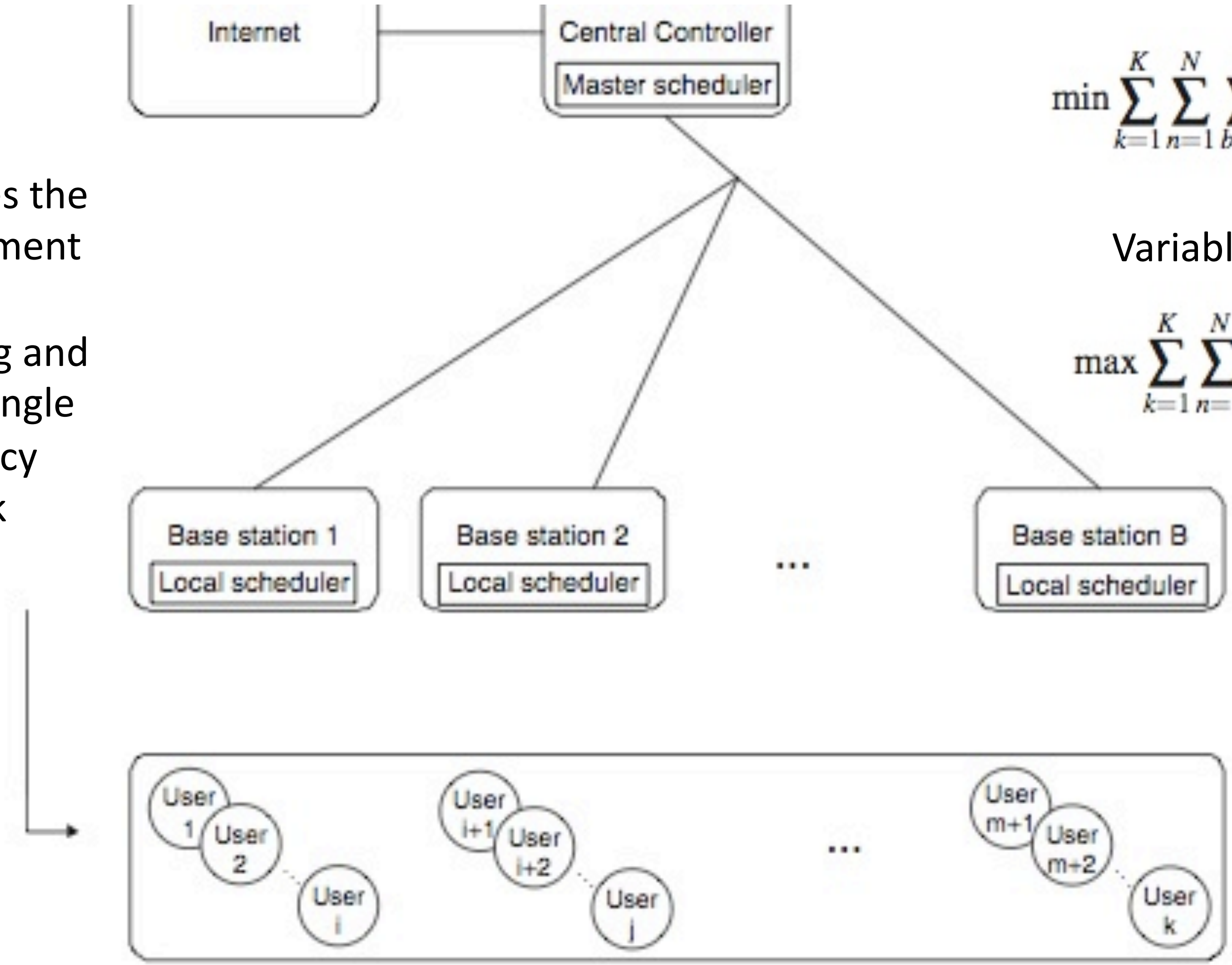
$$\{\bar{k}, \bar{n}\} = \arg\max_{k,n} \frac{r_{k,n}}{t_{k,n}},$$

user

Average throughput of each user for a subcarrier in a past window of length t.

Single Frequency Network

Removes the requirement for cell planning and called single frequency network



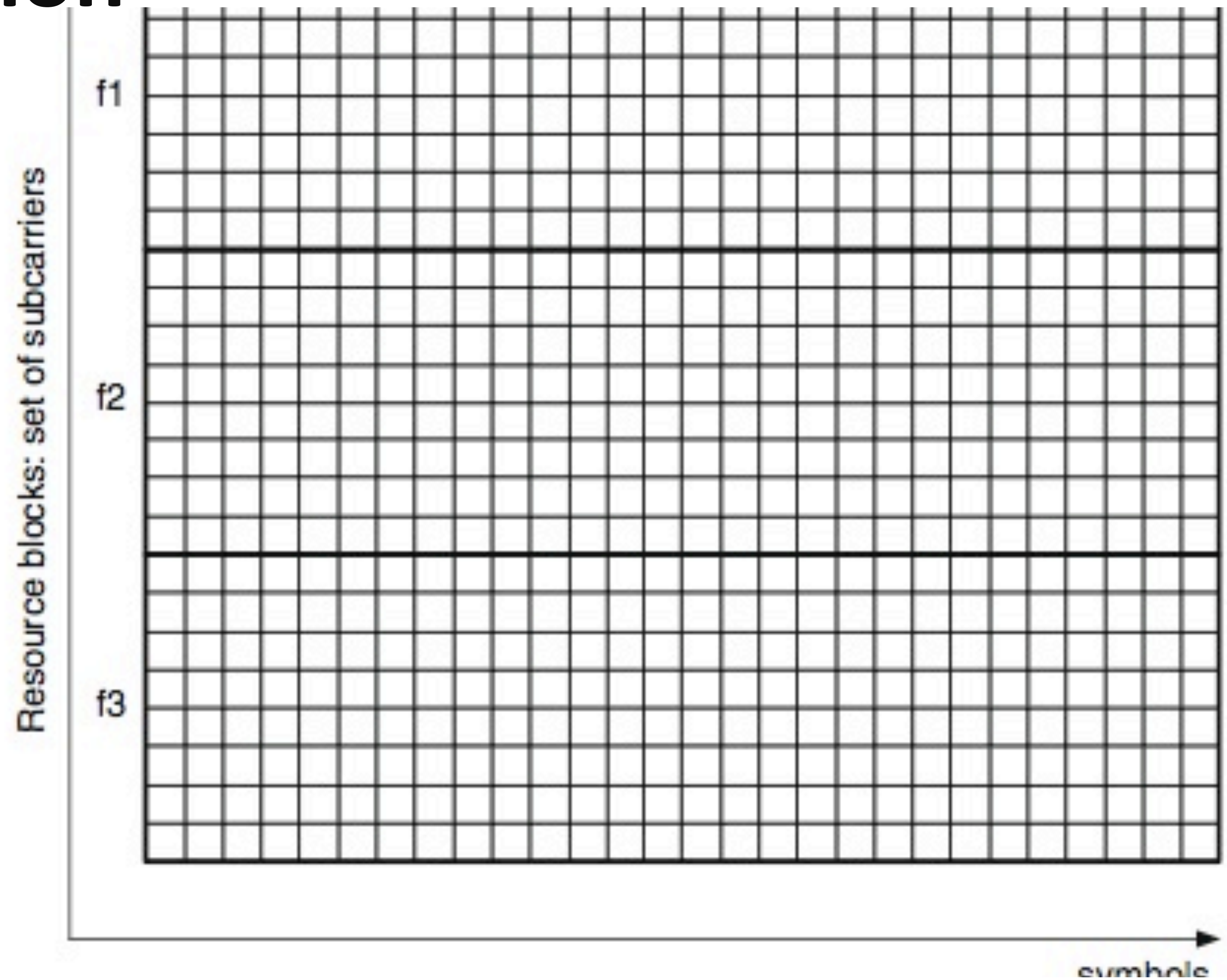
Fixed QoS

$$\min \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{b=1}^{B} \gamma_{k,n,b} P_{k,n,b}$$

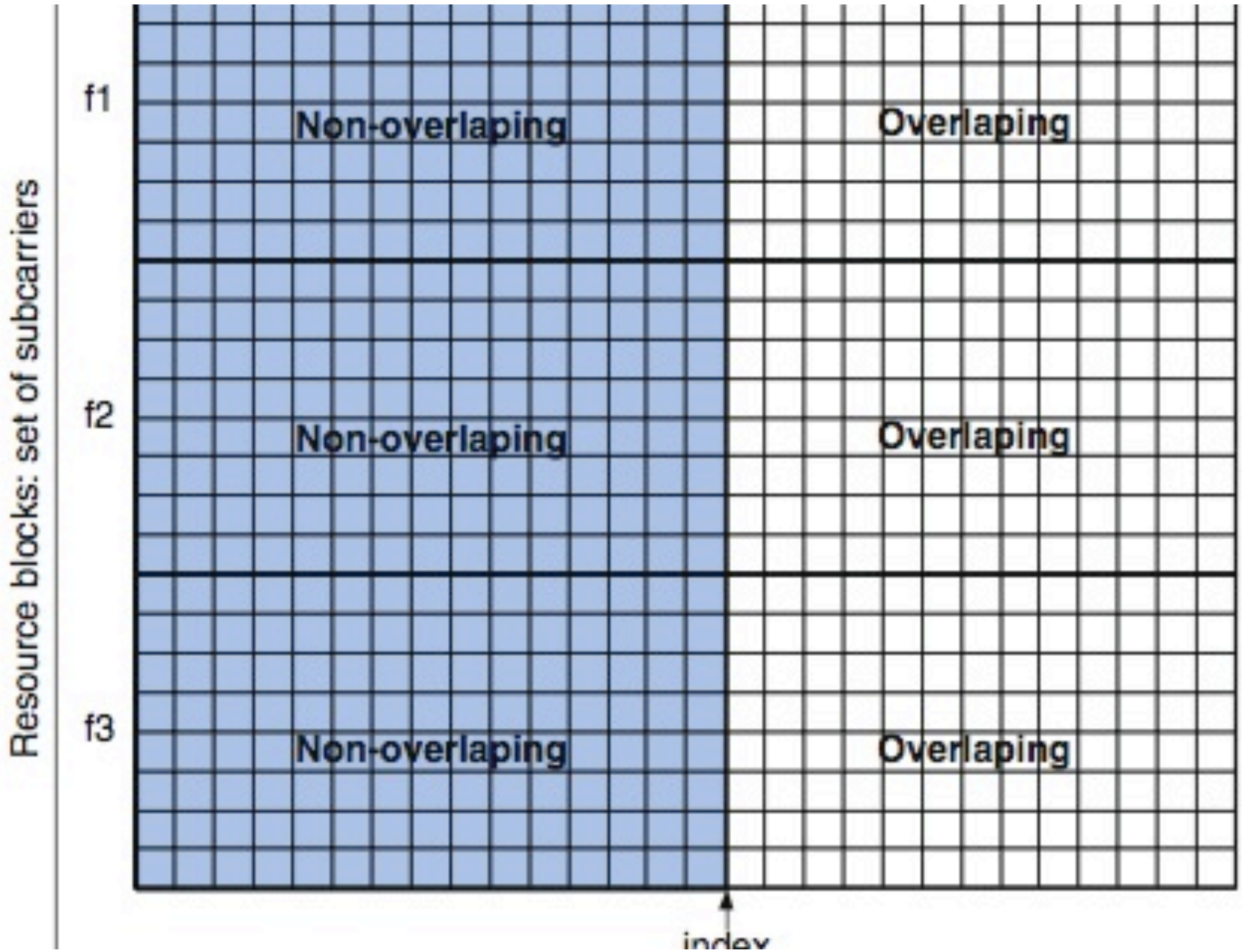
Variable QoS

$$\max \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{b=1}^{B} \gamma_{k,n,b} c_{k,n,b},$$

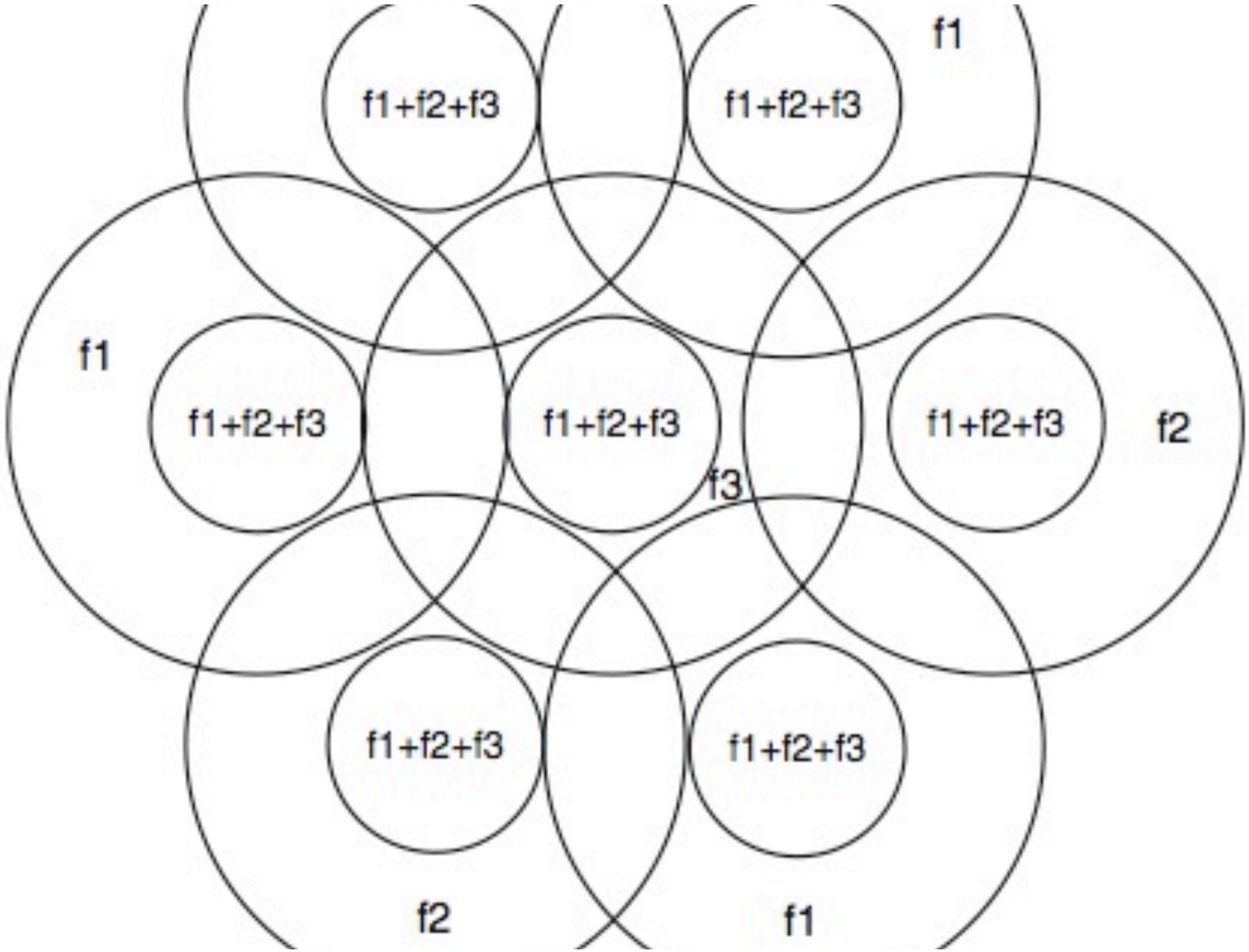
Single Frequency Network: Heuristic Solution



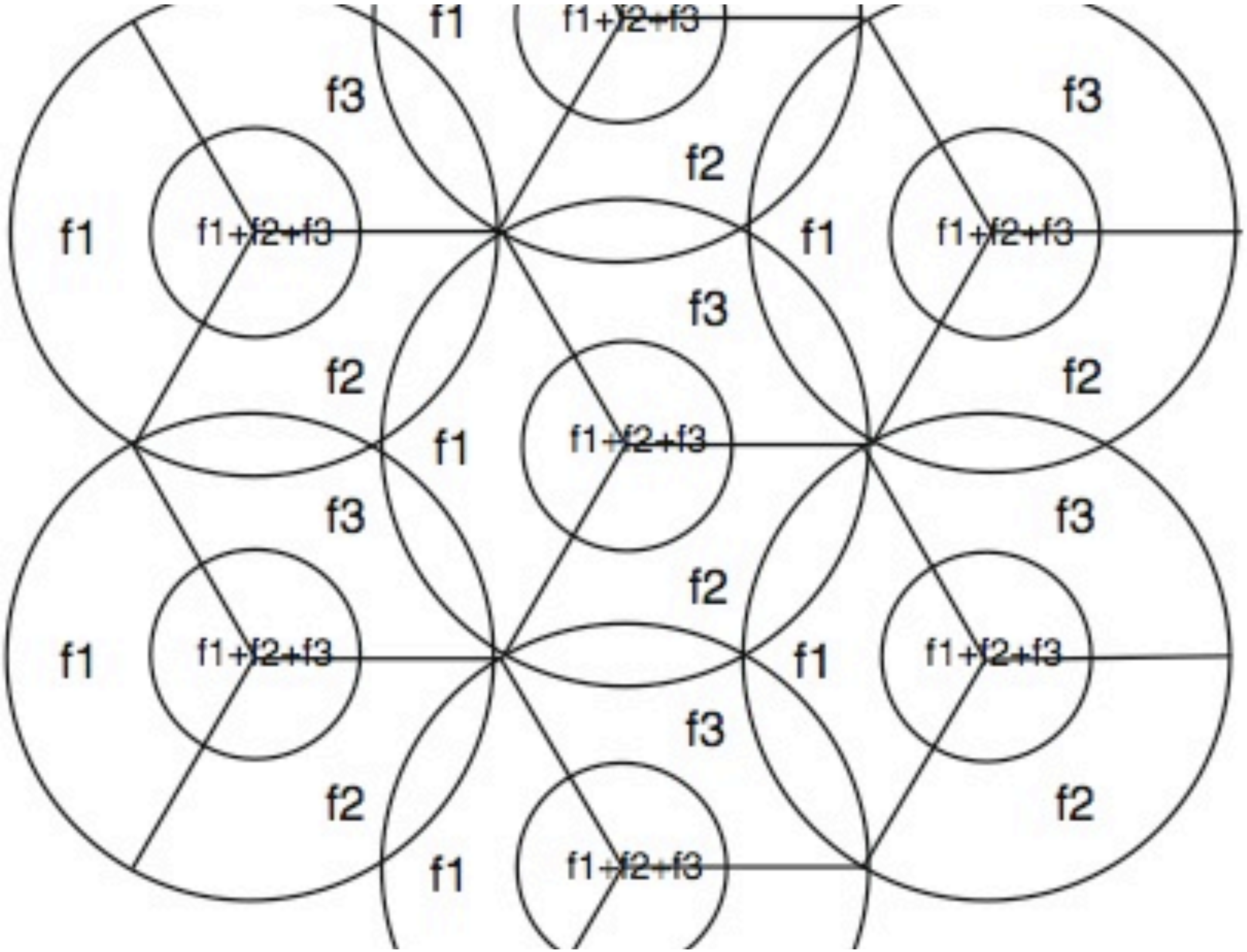
SFN: Frame Allocation



SFN: Omni Directional

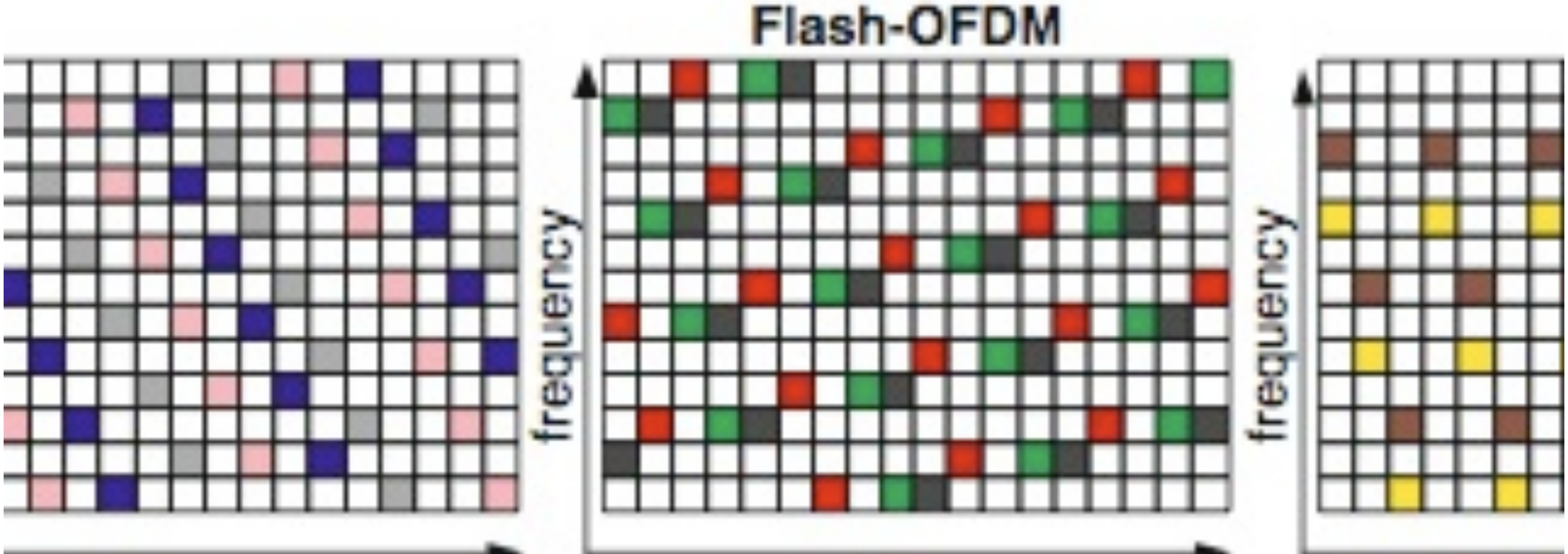


SFN: Sectoral



Flash OFDM

IEEE 802.20: Besides OFDMA, CDMA is used for interference averaging.



Flash-OFDM utilizes an hopping pattern in time and frequency in order to exploit interference diversity as in CDMA as well as frequency diversity. Interference diversity averages out the interference coming from more user, since interference coming solely from one user causes severe interference to each other. A hopping pattern is assigned to a user, which alternates the subcarriers at each symbol.

Latin Squares

Periodic hopping patterns consider frequency diversity and interference diversity. Frequency diversity is exploited by allocating subcarriers as spread as possible and alternate them every symbol time. Interference diversity also considers to allocate hop patterns that are as “apart” as possible from adjacent base stations. If there are N subcarriers then N can be selected as the hopping period and there can be N channels.

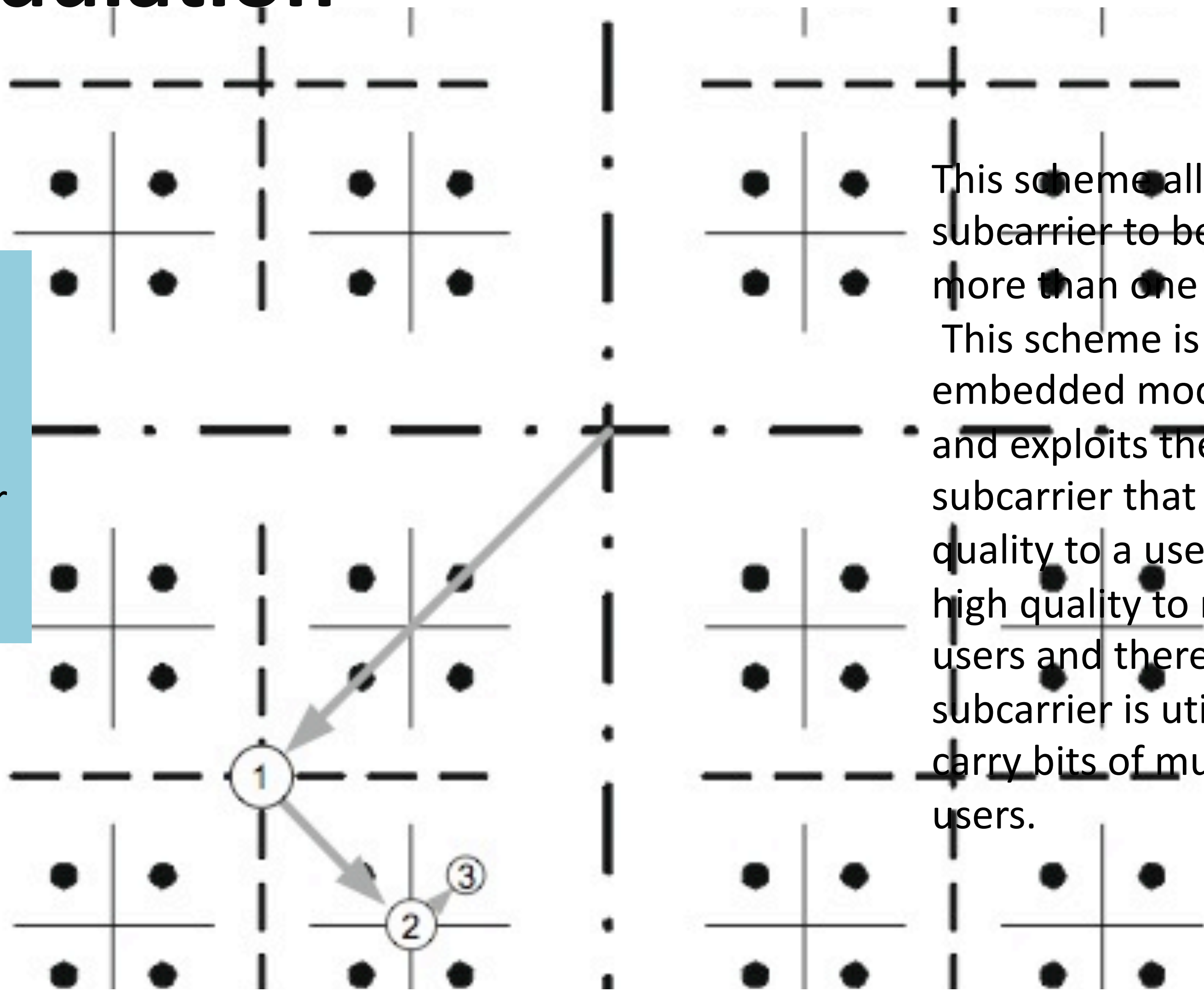
- Latin Square

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

- No. of Latin squares

N	No. of Latin squares
1	1
2	2
3	12
4	576
5	161280
6	812851200
7	61479419904000
8	108776032459082956800
9	5524751496156892842531225600
10	9982437658213039871725064756920320000
11	776966836171770144107444346734230682311065600000

Subcarrier Sharing: Embedded Modulation



Each carrier carries 6 bits for 64QAM modulation and each user uses only 2 out of 6.

This scheme allows a subcarrier to be used by more than one user.

This scheme is known as embedded modulation and exploits the fact that a subcarrier that is high quality to a user maybe high quality to multiple users and therefore that subcarrier is utilized to carry bits of multiple users.

References

- Mobile Broadband by M. Ergen

Lecture 7l

- MIMO

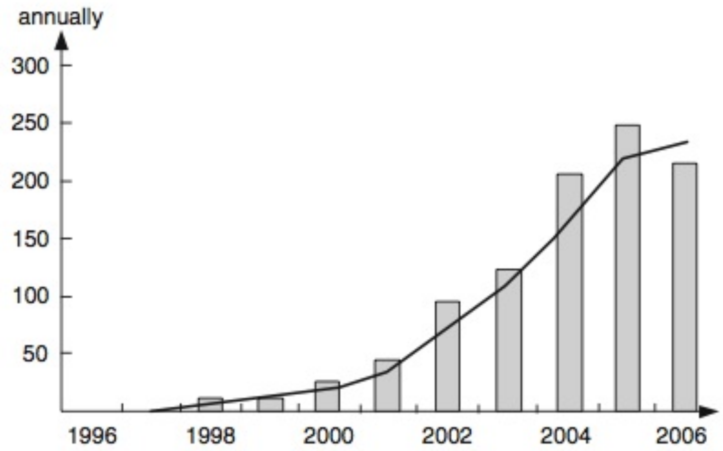


Fig. 6.1 MIMO patent applications per year. (Source: Marvedis)

Outline

- Introduction...why MIMO??
- Shannon capacity of MIMO systems
- The ”pipe” interpretation **Telatar, AT&T 1995**
- To exploit the MIMO channel
  - BLAST **Foschini, Bell Labs 1996**
  - Space Time Coding **Tarokh, Seshadri & Calderbank 1998**
  - Beamforming
- Comparisons & hardware issues
- Space time coding in 3G & EDGE **Release ’99**

Aspirations (Mathematical) of a System Designer

- High data rate

Achieve "Channel Capacity (C)"

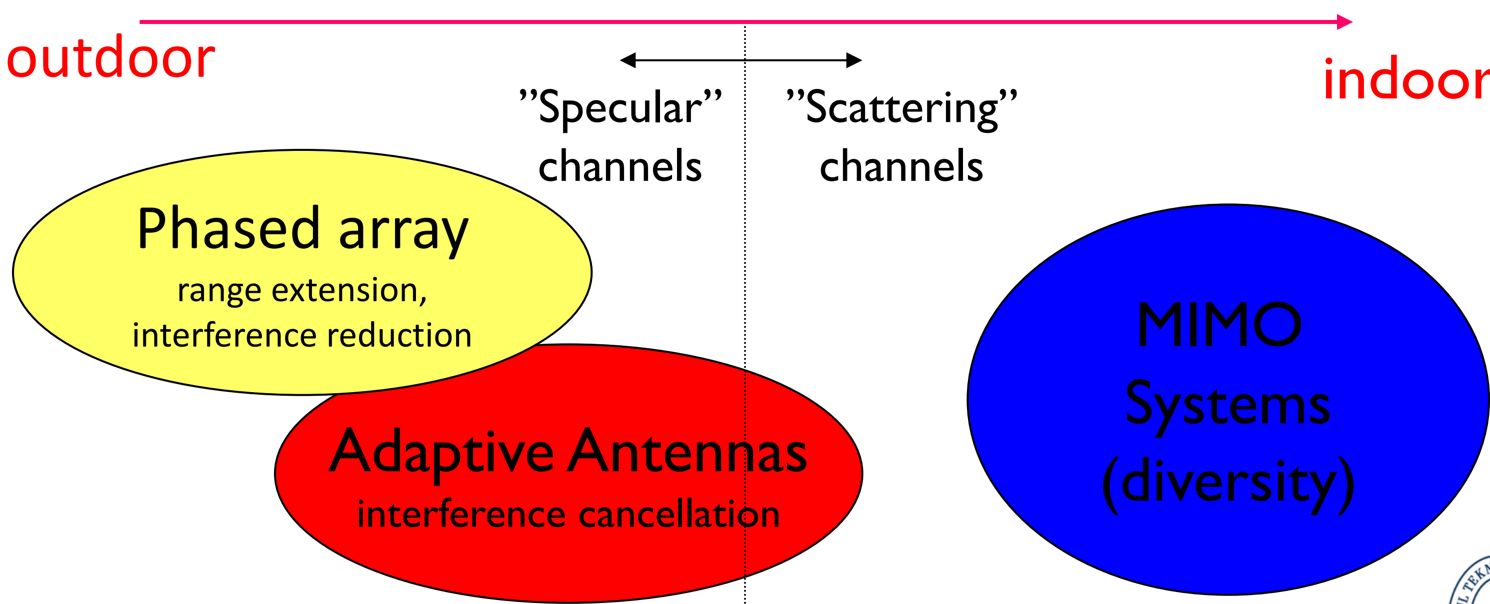
Quality → Minimize Probability of Error (Pe)

Real-life Issues →

- Minimize complexity/cost of implementation of proposed System
- Minimize transmission power required (translates into SNR)
- Minimize Bandwidth (frequency spectrum) Used

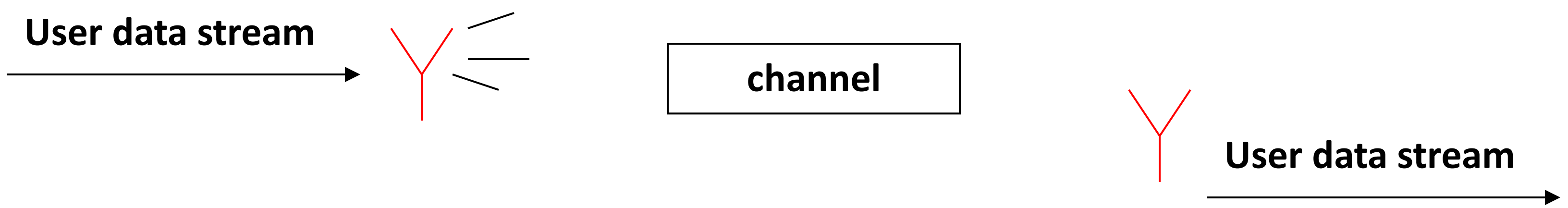
Why MIMO?

- Frequency and time processing are at limits
- Space processing is interesting because it does not increase bandwidth



Antenna Configurations

- Single-Input-Single-Output (SISO) antenna system



- Theoretically, the 1Gbps barrier can be achieved using this configuration if you are allowed to use much power and as much BW as you so please!
- Extensive research has been done on SISO under power and BW constraints. A combination a smart modulation, coding and multiplexing techniques have yielded good results but far from the 1Gbps barrier

MIMO Antenna Configuration

- Use multiple transmit and multiple receive antennas for a single user

- Now this system promises enormous data rates!

Shannon's Capacity (C)

- Given a unit of BW (Hz), the max error-free transmission rate is
- C = log2(1+SNR) bits/s/Hz
- Define
- R: data rate (bits/symbol)
- RS: symbol rate (symbols/second)
- w: allotted BW (Hz)
- Spectral Efficiency is defined as the number of bits transmitted per second per Hz
- R x RS   bits/s/Hz
-                W
- As a result of filtering/signal reconstruction requirements, RS ≤ W. Hence Spectral Efficiency = R if RS = W

- If I transmit data at a rate of R ≤ C, I can achieve an arbitrarily low Pe

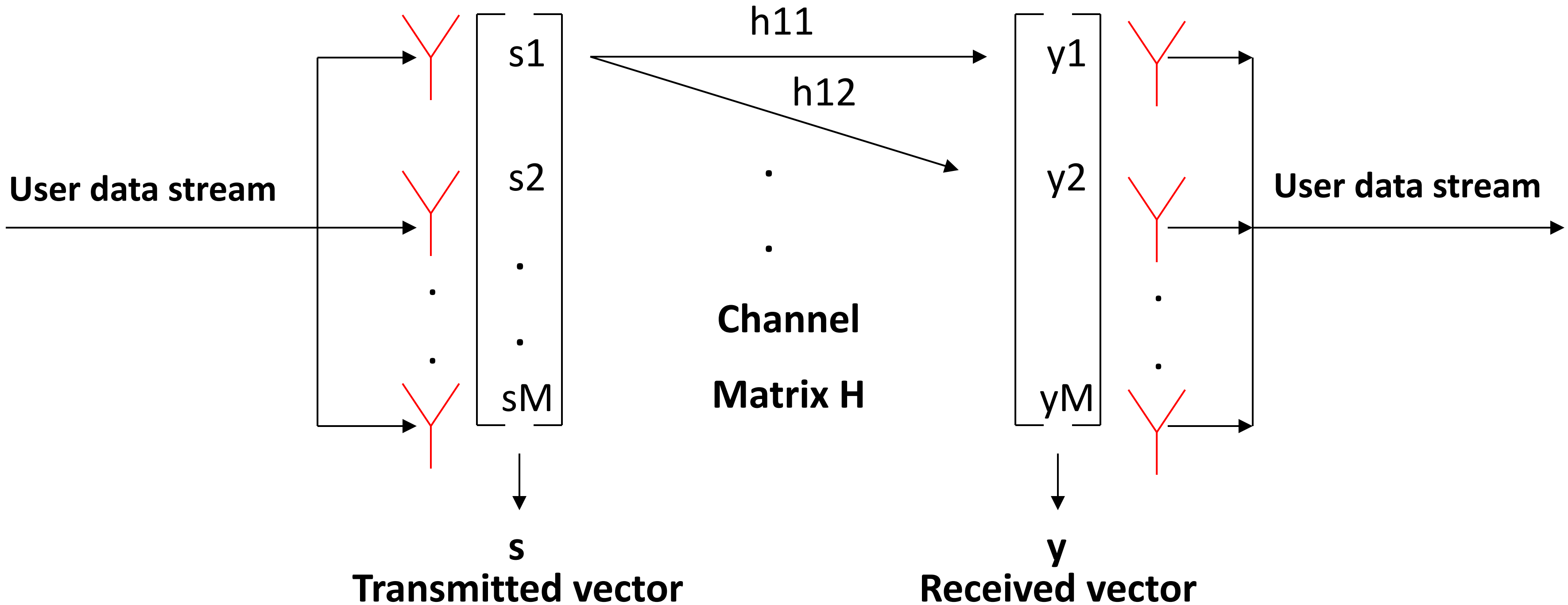
Spectral Efficiency

Scheme	b/s/Hz
BPSK	1
QPSK	2
16-QAM	4
64-QAM	6

- Spectral efficiencies of some widely used modulation schemes

- The Whole point: Given an acceptable Pe , realistic power and BW limits, MIMO Systems using smart modulation schemes provide much higher spectral efficiencies than traditional SISO

MIMO System Model



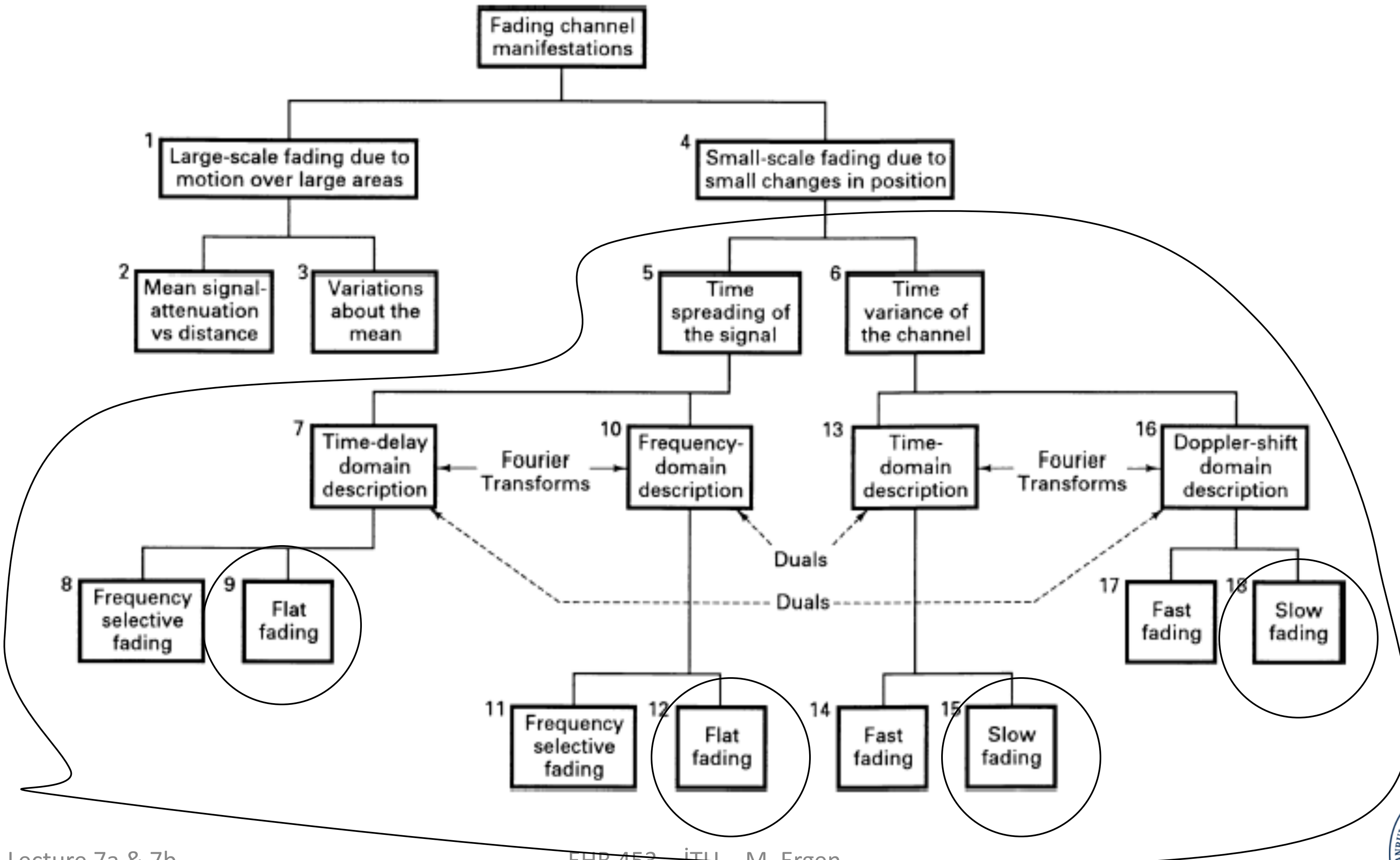
$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

Where **H** =

$$M_R \left\{ \underbrace{\begin{bmatrix} h11 & h21 & \cdots\cdots & hM1 \\ h12 & h22 & \cdots\cdots & hM2 \\ . & . & \cdots\cdots & . \\ h1M & h2M & \cdots\cdots & hMM \end{bmatrix}}_{M_T} \right.$$

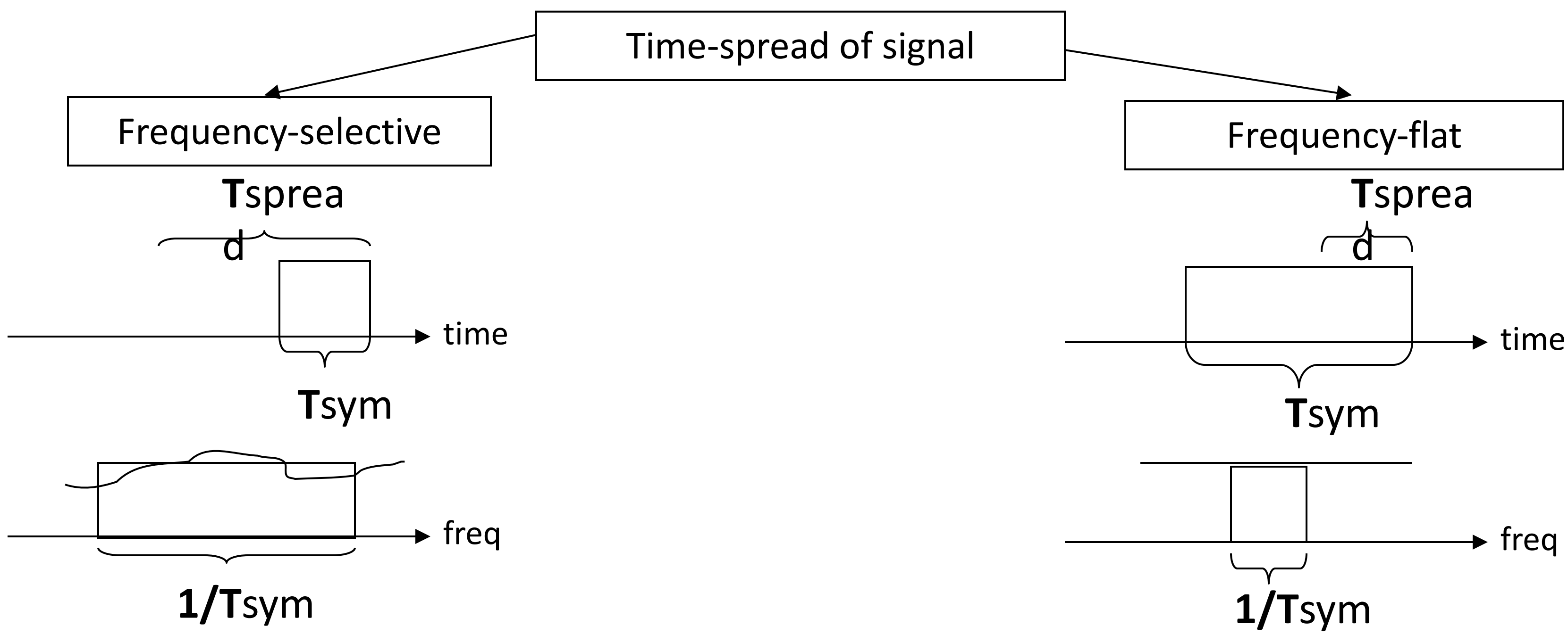
hij is a Complex Gaussian random variable that models fading gain between the ith transmit and jth receive antenna

Types of Channels



Fading Channels

- ***Fading*** **refers to changes in signal amplitude and phase caused by the channel as it makes its way to the receiver**
- **Define T_{spread} to be the time at which the last reflection arrives and T_{sym} to be the symbol time period**



Occurs for wideband signals (small Tsym)

TOUGH TO DEAL IT!

Occurs for narrowband signals (large Tsym)

EASIER! Fading gain is complex Gaussian

Multipaths NOT resolvable

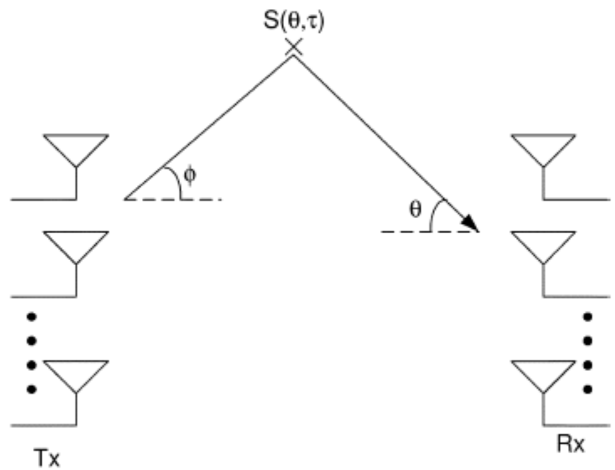
Channel Matrix H

- In addition, assume slow fading
- MIMO Channel Response

$$\mathbf{H}(\tau,t)=\begin{bmatrix} h_{1,1}(\tau,t) & h_{1,2}(\tau,t) & \cdots & h_{1,M_T}(\tau,t) \\ h_{2,1}(\tau,t) & h_{2,2}(\tau,t) & \cdots & h_{2,M_T}(\tau,t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{M_R,1}(\tau,t) & h_{M_R,2}(\tau,t) & \cdots & h_{M_R,M_T}(\tau,t) \end{bmatrix}.$$

Channel Time-variance

Time-spread



- **Taking into account slow fading, the MIMO channel impulse response is constructed as,**

$$\mathbf{H}(\tau) = \int_{-\pi}^{\pi}\int_{0}^{\tau_{\max}} S(\theta,\tau')\mathbf{a}(\theta)\mathbf{b}^T(\phi)g(\tau-\tau')d\tau' d\theta$$

- **Because of flat fading, it becomes,**

$$\mathbf{H}(\tau)=\left(\int_{-\pi}^{\pi}\int_{0}^{\tau_{\max}} S(\theta,\tau')\mathbf{a}(\theta)\mathbf{b}^T(\phi)d\tau' d\theta\right)g(\tau)=\mathbf{H}\,g(\tau)$$

a and b are transmit and receive array factor vectors respectively. S is the complex gain that is dependant on direction and delay. g(t) is the transmit and receive pulse shaping impulse response

- **With suitable choices of array geometry and antenna element patterns,**
  H(τ) = H which is an MR x MT matrix with complex Gaussian i. i. d random variables
- **Accurate for NLOS rich-scattering environments, with sufficient antenna spacing at transmitter and receiver with all elements identically polarized**

Capacity of MIMO Channels

- y = Hs + n
- Let the transmitted vector s be a random vector to be very general and n is normalized noise. Let the total transmitted power available per symbol period be P. Then,

- C = log 2 (IM + HQHH) b/s/Hz
- where Q = E{ssH} and trace(Q) < P according to our power constraint

- Consider specific case when we have users transmitting at equal power over the channel and the users are uncorrelated (no feedback available). Then,

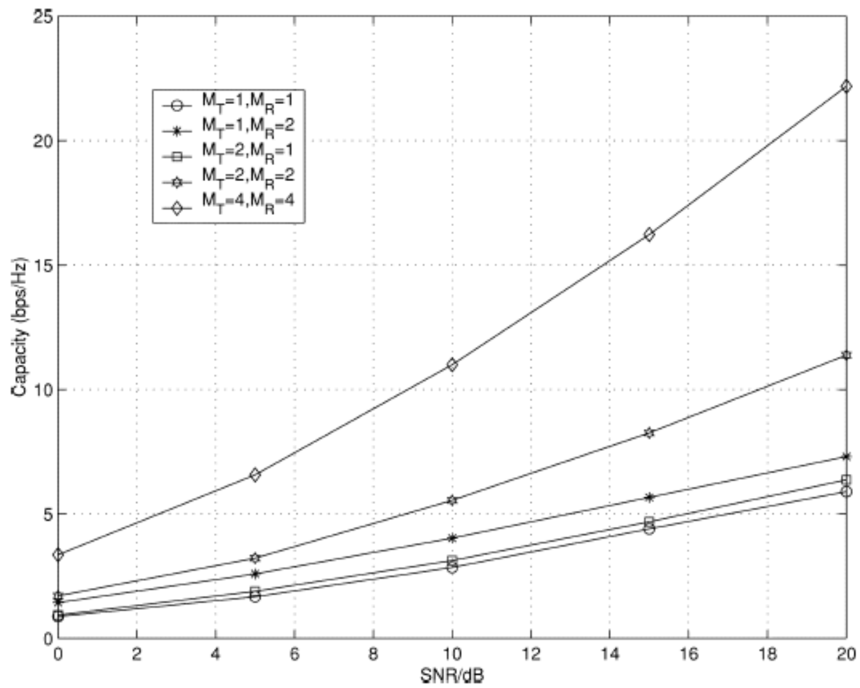
- CEP = log 2 [IM + (P/MT)HHH] b/s/Hz
- Telatar showed that this is the optimal choice for blind transmission

- Foschini and Telatar both demonstrated that as MT and MR grow,

- CEP = min (MT,MR) log 2 (P/MT) + constant b/s/Hz
- Note: When feedback is available, the Waterfilling solution is yields maximum capacity but converges to equal power capacity at high SNRs

Capacity (contd)

- The capacity expression presented was over one realization of the channel. Capacity is a random variable and has to be averaged over infinite realizations to obtain the true ergodic capacity. Outage capacity is another metric that is used to capture this



- **So MIMO promises enormous rates theoretically! Can we exploit this practically?**

MIMO Design Criterion

- MIMO Systems can provide two types of gain

Spatial Multiplexing Gain

- Maximize transmission rate (optimistic approach)
- Use rich scattering/fading to your advantage

Diversity Gain

- Minimize Pe (conservative approach)
- Go for Reliability / QoS etc
- Combat fading

- **If only I could have both! As expected, there is a tradeoff**
- **System designs are based on trying to achieve either goal or a little of both**

Diversity

- Each pair of transmit-receive antennas provides a signal path from transmitter to receiver. By sending the SAME information through different paths, multiple independently-faded replicas of the data symbol can be obtained at the receiver end. Hence, more reliable reception is achieved
- A diversity gain d implies that in the high SNR region, my Pe decays at a rate of 1/SNRd as opposed to 1/SNR for a SISO system
- The maximal diversity gain dmax is the total number of independent signal paths that exist between the transmitter and receiver
- For an (MR,MT) system, the total number of signal paths is MRMT
-
- $1 \leq d \leq d_{max} = M_R M_T$
- The higher my diversity gain, the lower my Pe

Spatial Multiplexing

$$y = Hs + n \rightarrow y' = Ds' + n' \text{ (through SVD on H)}$$

where D is a diagonal matrix that contains the eigenvalues of HH^H

- Viewing the MIMO received vector in a different but equivalent way,

$$C_{EP} = \log_2 [I_M + (P/M_T)DD^H] = \sum_{i=1}^{m} \log_2 [1 + (P/M_T)\lambda_i] \text{ b/s/Hz}$$

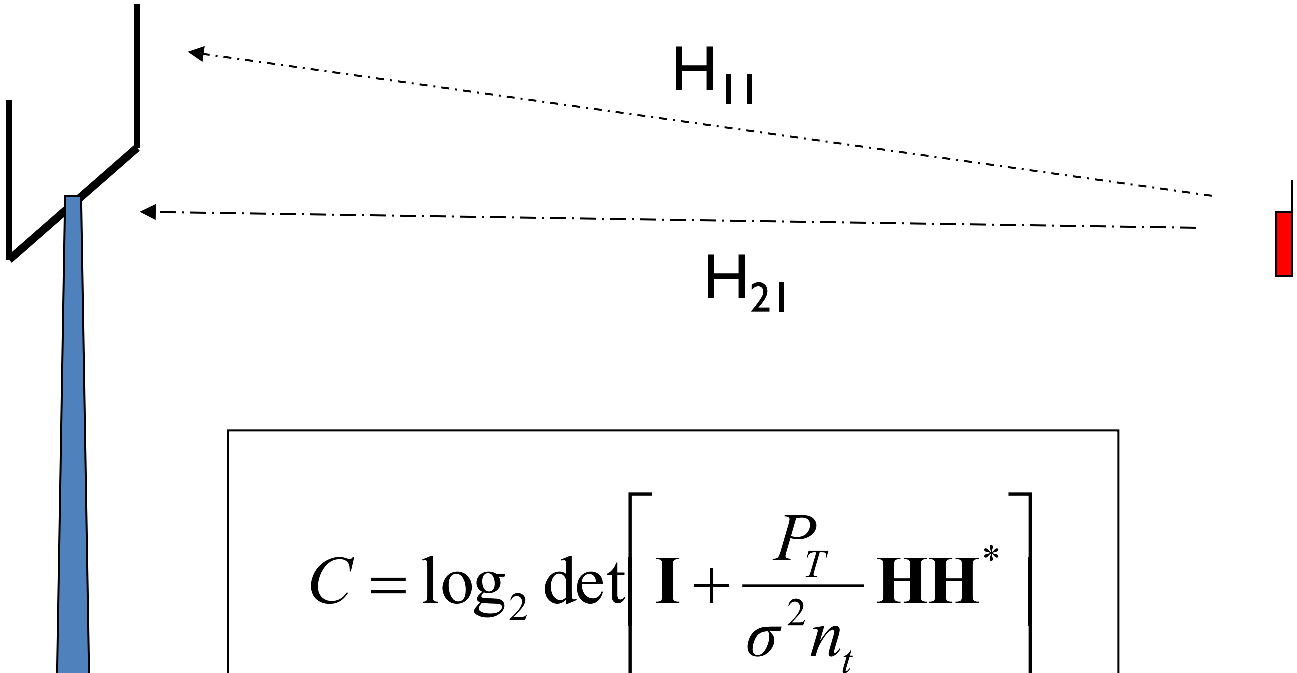
- Equivalent form tells us that an (M_T,M_R) MIMO channel opens up $m = \min(M_T,M_R)$ independent SISO channels between the transmitter and the receiver

- So, intuitively, I can send a maximum of m different information symbols over the channel at any given time

Initial Assumptions

- Flat fading channel (Bcoh>> 1/ Tsymb)
- Slowly fading channel (Tcoh>> Tsymb)
- nr receive and nt transmit antennas
- Noise limited system (no CCI)
- Receiver estimates the channel perfectly
- We consider space diversity only

Receive Diversity



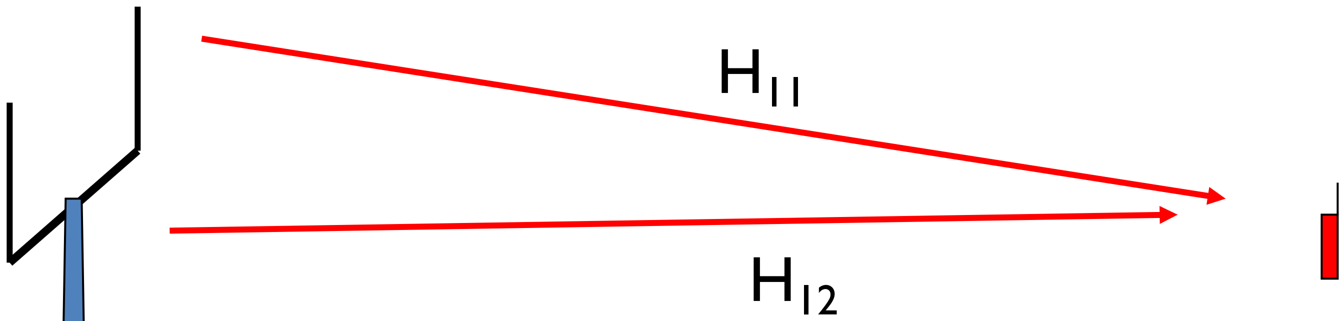
$$C = \log_2 \det \left[\mathbf{I} + \frac{P_T}{\sigma^2 n_t} \mathbf{H}\mathbf{H}^* \right]$$

$$= \log_2[1 + (P_T/\sigma^2) \cdot |\mathbf{H}|^2] \quad [\text{bit}/(\text{Hz} \cdot \text{s})]$$

Capacity increases logarithmically with number of receive antennas...

$\mathbf{H} = [\, H_{11}\ H_{21}]$

Transmit Diversity

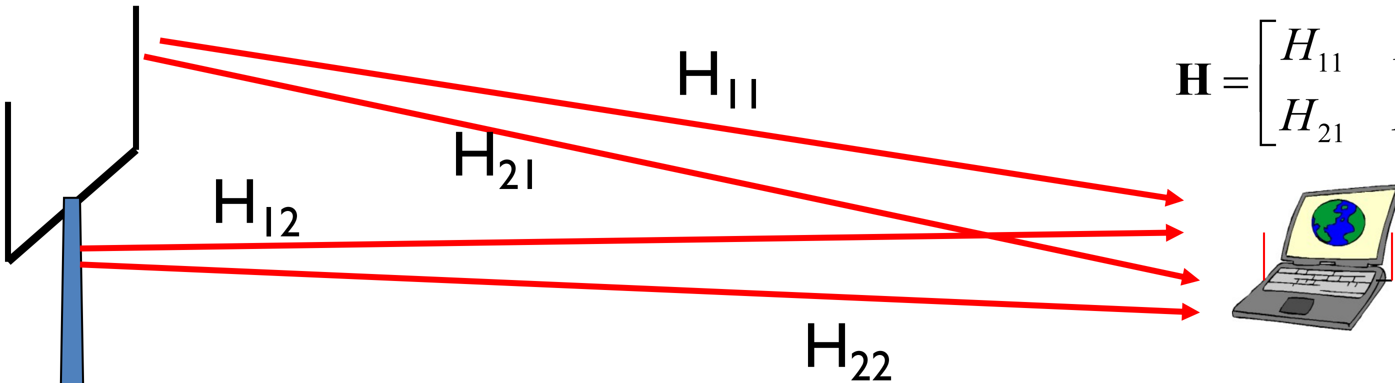


$$C_{diversity} = \log_2(1 + (P_T/2\sigma^2) \cdot |\mathbf{H}|^2) \quad [\text{bit}/(\text{Hz} \cdot \text{s})]$$

$$C_{beamforming} = \log_2(1 + (P_T/\sigma^2) \cdot |\mathbf{H}|^2) \quad [\text{bit}/(\text{Hz} \cdot \text{s})]$$

- 3 dB SNR increase if transmitter knows **H**
- Capacity increases logarithmically with n_t

MIMO



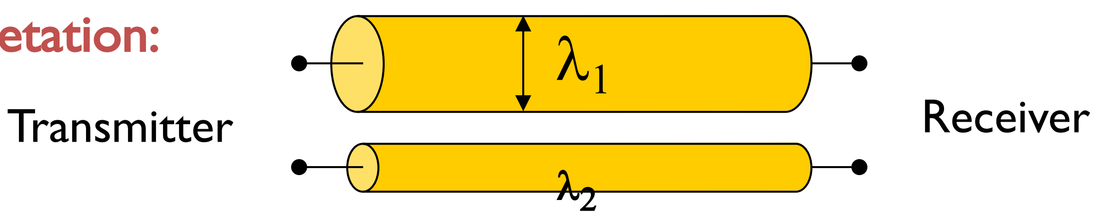
$$\mathbf{H} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}$$

$$C_{diversity} = \log_2 \det[I + (P_T/2\sigma^2) \cdot HH^\dagger] =$$

Where the λ_i are the eigenvalues to $HH^\dagger$

$$= \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_1\right] + \log_2\left[1 + \frac{P_T}{2\sigma^2}\lambda_2\right]$$

Interpretation:



$m = \min(n_r, n_t)$ parallel channels,
equal power allocated to each "pipe"

MIMO capacity in general

H unknown at TX

$$C = \log_2 \det\left[I + \frac{P_T}{\sigma^2 n_t} HH^* \right] =$$

$$= \sum_{i=1}^{m} \log_2 \left[1 + \frac{P_T}{\sigma^2 n_t} \lambda_i \right]$$

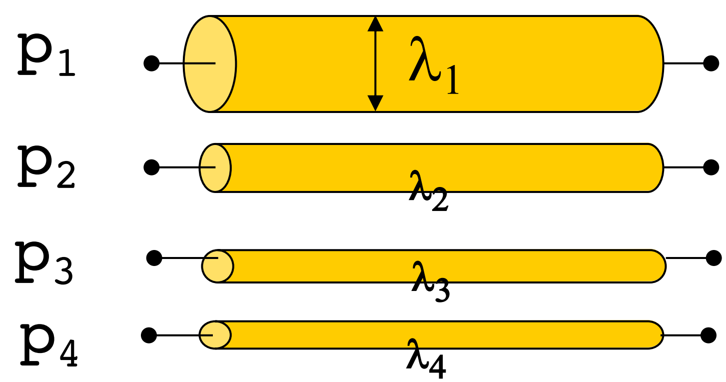
$$m = \min(n_r, n_t)$$

H known at TX

$$C = \sum_{i=1}^{m} \log_2 \left[1 + \frac{p_i \lambda_i}{\sigma^2} \right]$$

Where the power distribution over "pipes" are given by a water filling solution

$$P_T = \sum_{i=1}^{m} p_i = \sum_{i=1}^{m} \left(\nu - \frac{1}{\lambda_i} \right)^+$$



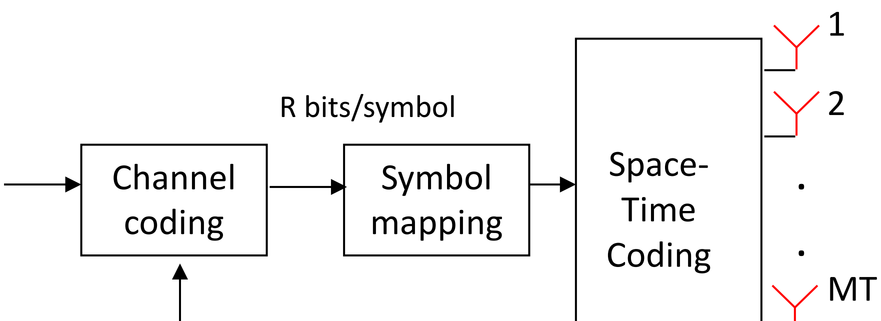
The Channel Eigenvalues

Orthogonal channels $HH^{\dagger} = I$, $\lambda_1 = \lambda_2 = \ldots = \lambda_m = 1$

$$C_{\textbf{diversity}} = \sum_{i=1}^{m} \log_2 \left[1 + \frac{P_T}{\sigma^2 n_t} \lambda_i \right] = \min(n_t, n_r) \cdot \log_2 (1 + P_T / \sigma^2 n_t)$$

- Capacity increases linearly with $\min(n_r, n_t)$
- An equal amount of power P_T/n_t is allocated to each "pipe"

Practical System



Redundancy in time

Coding rate = rc

Space- time redundancy over T symbol periods

Spatial multiplexing gain = rs

rs : number of different symbols N transmitted in T symbol periods

rs = N/T

Non-redundant portion of symbols

$$\text{Spectral efficiency} = \frac{(R*rc \text{ info bits/symbol})(rs)(Rs \text{ symbols/sec})}{w}$$

$$= Rrcrs \text{ bits/s/Hz assuming } Rs = w$$

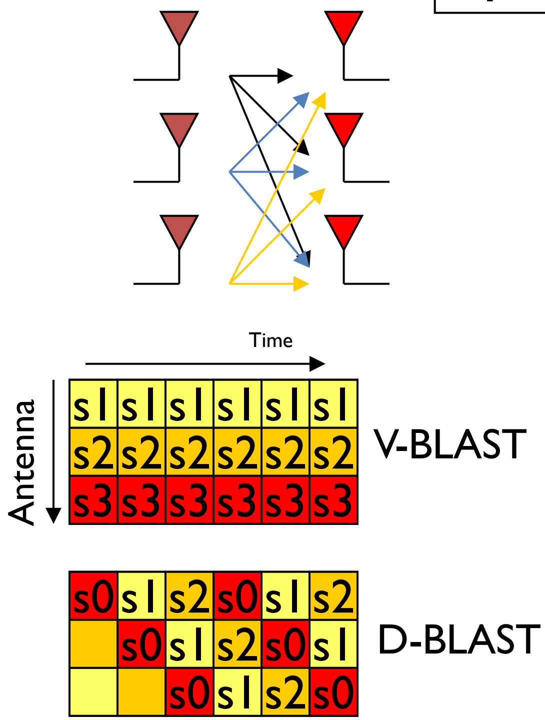
rs is the parameter that we are concerned about: $0 \le rs \le MT$

**** If rs = MT, we are in spatial multiplexing mode (max transmission rate)**

****If rs ≤ 1, we are in diversity mode**

BLAST

Bell Labs **La**yered **S**pace **T**ime Architecture

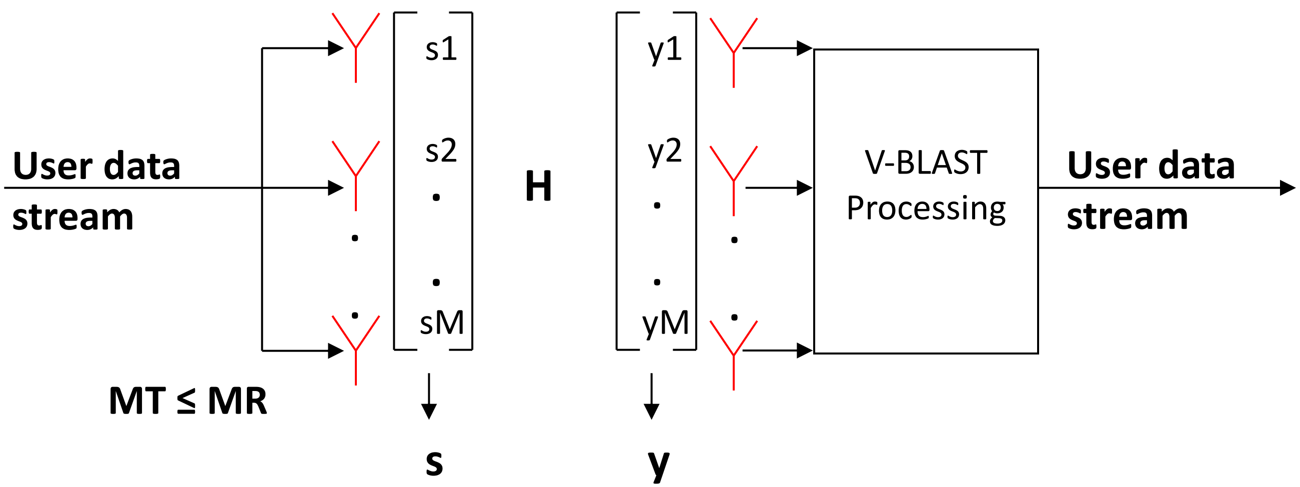


- $n_r \geq n_t$ required
- Symbol by symbol detection. Using nulling and symbol cancellation
- V-BLAST implemented -98 by Bell Labs (40 bps/Hz)
- If one "pipe" is bad in BLAST we get errors ...

{G.J.Foschini, Bell Labs Technical Journal 1996 }

V-BLAST (Vertical) – Spatial Multiplexing

- This is the only architecture that goes all out for maximum rate. Hope the channel helps me out by 'splitting' my info streams!



initialization:

$$
\begin{aligned}
i &\leftarrow 1 \\
\mathbf{G}_1 &= \mathbf{H}^{+} \\
k_1 &= \underset{j}{\operatorname{argmin}} \|(\mathbf{G}_1)_j\|^2
\end{aligned}
$$

recursion:

$$
\begin{aligned}
\mathbf{w}_{k_i} &= (\mathbf{G}_i)_{k_i} \\
y_{k_i} &= \mathbf{w}_{k_i}^T \mathbf{r}_i \\
\hat{a}_{k_i} &= Q(y_{k_i}) \\
\mathbf{r}_{i+1} &= \mathbf{r}_i - \hat{a}_{k_i} (\mathbf{H})_{k_i} \\
\mathbf{G}_{i+1} &= \mathbf{H}_{\bar{k}_i}^{+} \\
k_{i+1} &= \underset{j \notin \{k_1 \cdots k_i\}}{\operatorname{argmin}} \|(\mathbf{G}_{i+1})_j\|^2 \\
i &\leftarrow i + 1
\end{aligned}
$$

- **Split data into MT streams → maps to symbols → send**
- **Assume receiver knows H**
- **Uses old technique of ordered successive cancellation to recover signals**
- **Sensitive to estimation errors in H**
- **rs = MT because in one symbol period, you are sending MT different symbols**

D-BLAST – (Diagonal)

- In D-BLAST, the input data stream is divided into sub streams which
- are coded, each of which is transmitted on different antennas time
- slots in a diagonal fashion
- For example, in a (2,2) system

$$\begin{bmatrix} 0 & \boldsymbol{x}_1^{(1)} & \boldsymbol{x}_1^{(2)} & \cdots \\ \boldsymbol{x}_2^{(1)} & \boldsymbol{x}_2^{(2)} & \boldsymbol{x}_2^{(3)} & \cdots \end{bmatrix}$$

MT ≤ MR

- **receiver first estimates $x2^{(1)}$ and then estimates $x1^{(1)}$ by treating $x2^{(1)}$ as interference and nulling it out**
- **The estimates of $x2^{(1)}$ and $x1^{(1)}$ are fed to a joint decoder to decode the first substream**

- **After decoding the first substream, the receiver cancels the contribution of this substream from the received signals and starts to decode the next substream, etc.**
- **Here, an overhead is required to start the detection process; corresponding to the 0 symbol in the above example**
- **Receiver complexity high**

Alamouti's Scheme - Diversity

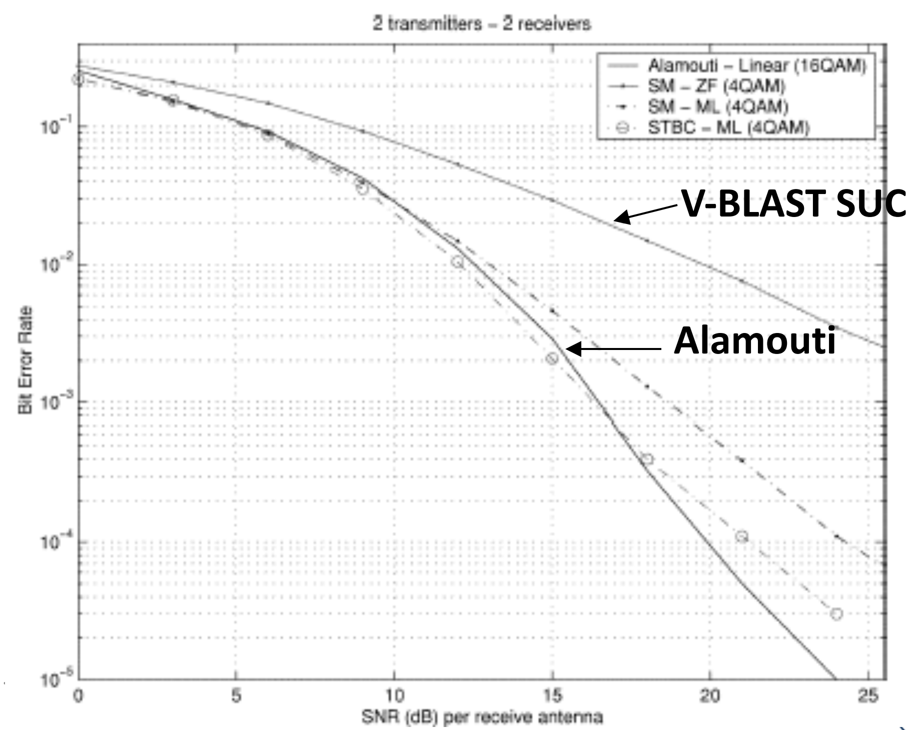
- Transmission/reception scheme easy to implement
- Space diversity because of antenna transmission. Time diversity because of transmission over 2 symbol periods
- Consider (2, MR) system

$$\begin{bmatrix} x_1 & -x_2^\dagger \\ x_2 & x_1^\dagger \end{bmatrix}$$

- **Receiver uses combining and ML detection**
- **rs = 1**

• If you are working with a (2,2) system, stick with Alamouti!

• Widely used scheme: CDMA 2000, WCDMA and IEEE 802.16-2004 OFDM-256



Comparisons

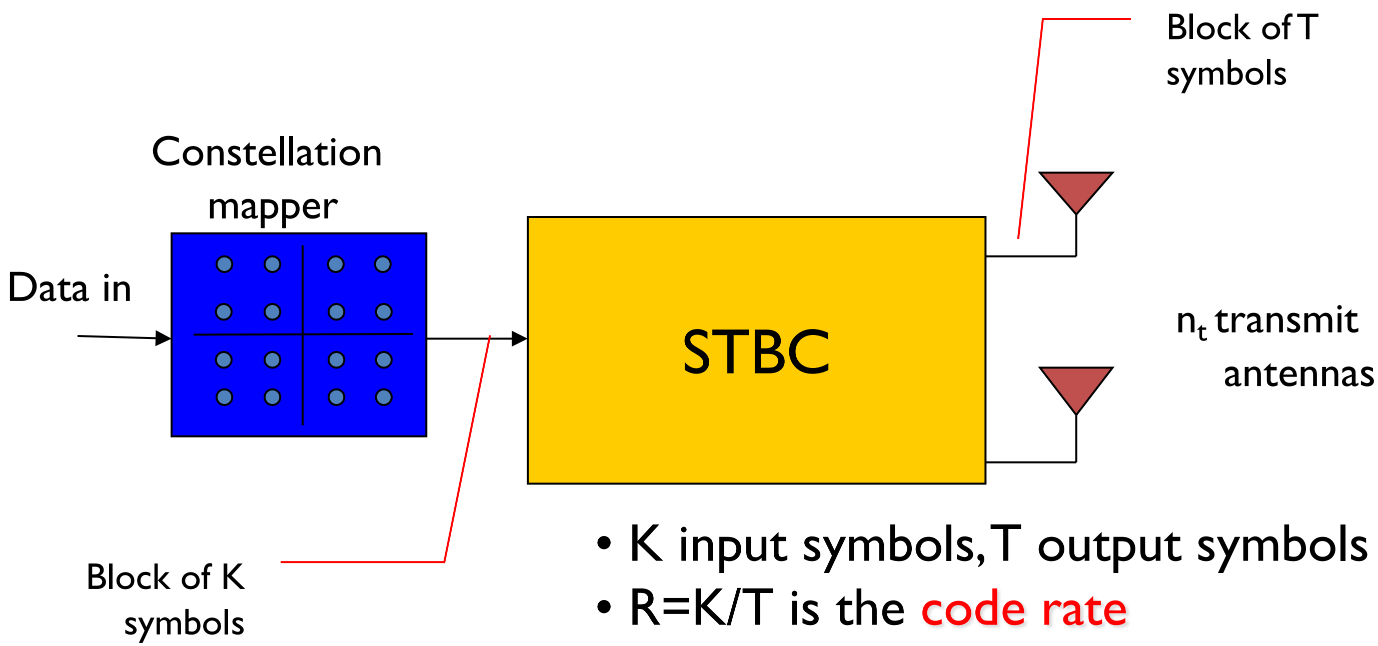
Scheme	Spectral Efficiency	P_e	Implementation Complexity
V-BLAST	HIGH	HIGH	LOW
D-BLAST	MODERATE	MODERATE	HIGH
ALAMOUTI	LOW	LOW	LOW

Space Time Coding

- Use parallel channel to obtain diversity not spectral efficiency as in BLAST
- Space-Time trellis codes : coding and diversity gain (require Viterbi detector)
- Space-Time block codes : diversity gain (use outer code to get coding gain)
- $n_r = 1$ is possible
- Properly designed codes acheive diversity of $n_r\, n_t$

*{V.Tarokh, N.Seshadri, A.R.Calderbank
Space-time codes for high data rate wireless communication:
Performance Criterion and Code Construction
, IEEE Trans. On Information Theory March 1998 }

Orthogonal Space-time Block Codes



- K input symbols, T output symbols $T \geq K$
- R=K/T is the code rate
- If R=1 the STBC has full rate
- If T= n_t the code has minimum delay
- Detector is linear !!!

*{V.Tarokh, H.Jafarkhani, A.R.Calderbank
Space-time block codes from orthogonal designs,
IEEE Trans. On Information Theory June 1999 }

STBC for 2 Transmit Antennas

Full rate and minimum delay

$$[\ c_0\ c_1\ ] \Rightarrow \begin{bmatrix} c_0 & -c_1^* \\ c_1 & c_0^* \end{bmatrix}$$

↓ Antenna

→ Time

Assume 1 RX antenna:

Received signal at time 0 $\quad r_0 = h_1 c_0 + h_2 c_1 + n_0$

Received signal at time 1 $\quad r_1 = -h_1 c_1^* + h_2 c_0^* + n_1$

$$\mathbf{r} = \overline{\mathbf{H}}\mathbf{c} + \mathbf{n}$$

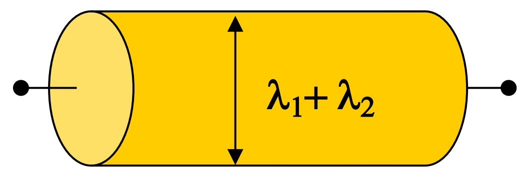
$$\mathbf{r} = \begin{bmatrix} r_0 \\ r_1^* \end{bmatrix}, \quad \overline{\mathbf{H}} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}, \quad \mathbf{n} = \begin{bmatrix} n_0 \\ n_1^* \end{bmatrix}, \quad \mathbf{c} = \begin{bmatrix} c_0 \\ c_1 \end{bmatrix}$$

$$\tilde{\mathbf{r}} = \overline{\mathbf{H}}^* \mathbf{r} = \underbrace{\overline{\mathbf{H}}^* \overline{\mathbf{H}}}\mathbf{c} + \overline{\mathbf{H}}^* \mathbf{n} = \left\| \mathbf{H} \right\|_F^2 \mathbf{c} + \tilde{\mathbf{n}}$$

Diagonal matrix due to orthogonality

The MIMO/ MISO system is in fact transformed to an equivalent SISO system with SNR

$SNR_{eq} = || H ||_F^2 \; SNR/n_t$



$|| H ||_F^2 = \lambda_1 + \lambda_2$

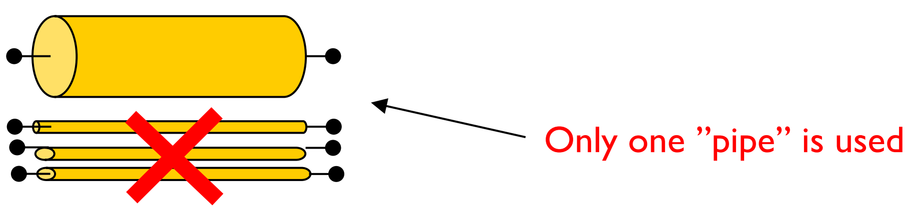
MIMO With Beamforming

Requires that channel **H** is known at the transmitter

Is the capacity-optimal transmission strategy if

$$\frac{1}{\lambda_2} - \frac{1}{\lambda_1} \geq SNR$$

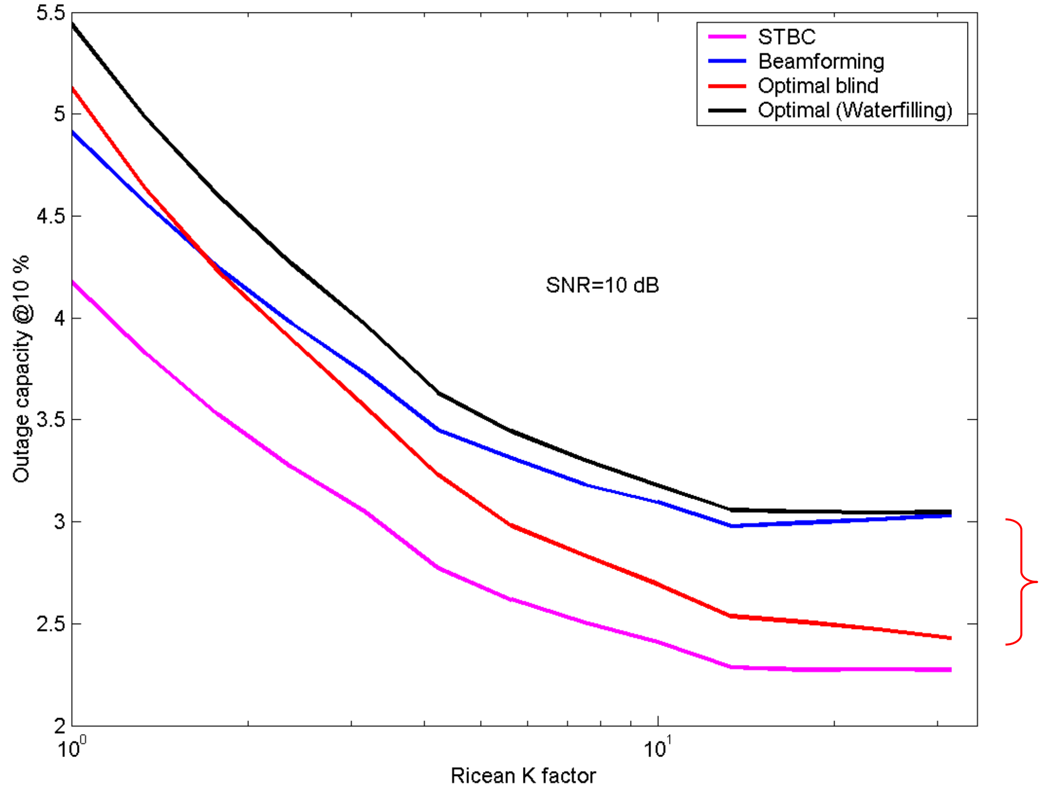
Which is often true for line of sight (LOS) channels



$C_{beamforming} = \log_2(1+SNR \cdot \lambda_1)$ [bit/(Hz ·s)]

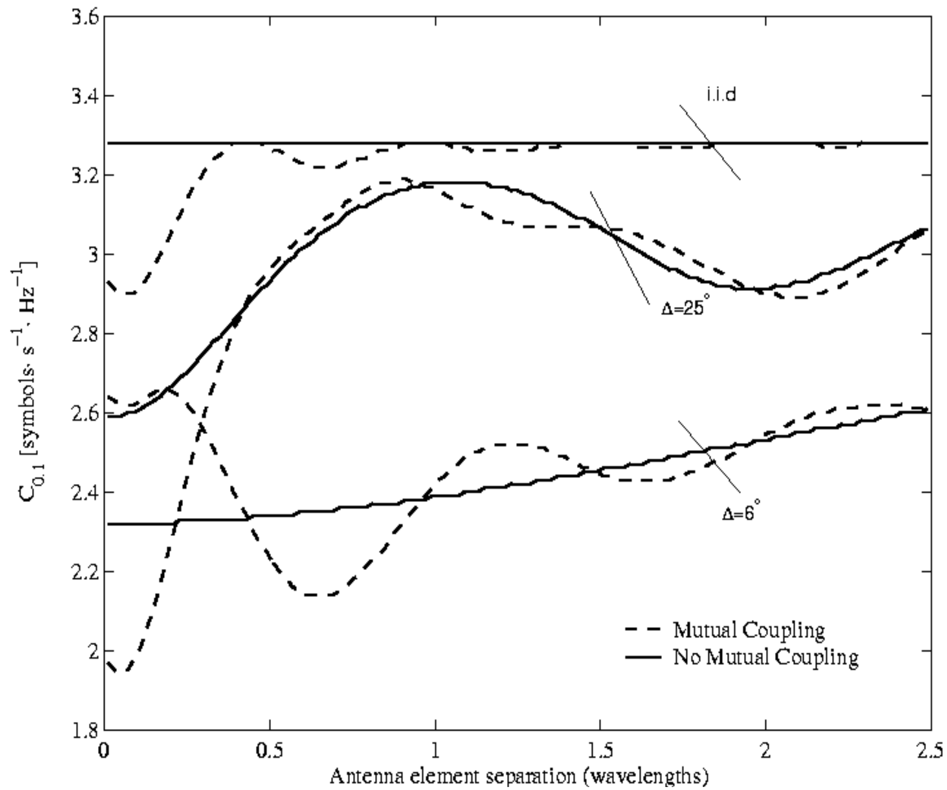
Comparisons...

2 * 2 system. With specular component (Ricean fading)



One dominating eigenvalue. BF puts all energy into that "pipe"

Correlated channels/mutual coupling



When angle spread (Δ) is small, we have a dominating eigenvalue.
The mutual coupling actually improves the performance of the STBC by making the eigenvalues ”more equal” in magnitude.

WCDMA Transmit Diversity Concept

(3GPP Release '99 with 2 TX antennas)

- 2 modes
  - Open loop *(STTD)*
  - Closed loop (1 bit / slot feedback)
    - Submode 1 (1 phase bit)
    - Submode 2 (3 phase bits / 1 gain bit)

Open loop mode is exactly the 2 antenna STBC

$$\begin{bmatrix} s_0 & -s_1^* \\ s_1 & s_0^* \end{bmatrix}$$

<u>The feedback bits (1500 Hz) determines the beamformer weights</u>

Submode 1 Equal power and bit chooses phase between {0,180} / {90/270}

Submode 2 Bit one chooses power division {0.8 , 0.2} / {0.2 , 0.8} and 3 bits chooses phase in an 8-PSK constellation

Message

- Channel capacity increases linearly with $\min(n_r, n_t)$
- STBC is in the 3GPP WCDMA proposal

References

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