Spatial Diversity

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Contents

1. Introduction to Diversity Techniques

- "Diversity" = "state of being varied, variety" [Oxford Advanced Learner's Dictionary].
- The basic concept of diversity: transmit the signal via several independent diversity branches to get independent signal replicas via
  - time diversity
  - frequency diversity
  - space diversity
  - polarization diversity.

⇨ High probability: all signals not fade simultaneously.

⇨ High probability: the deepest fades can be avoided.

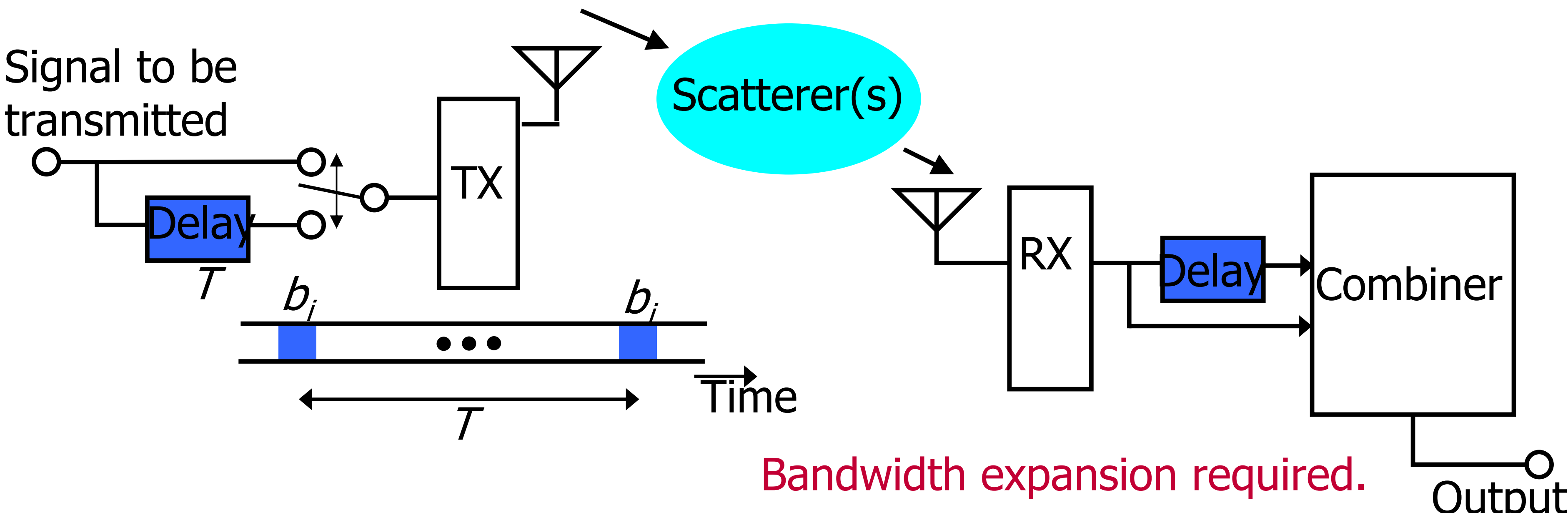
⇨ Protection against fading.

Diversity Domains

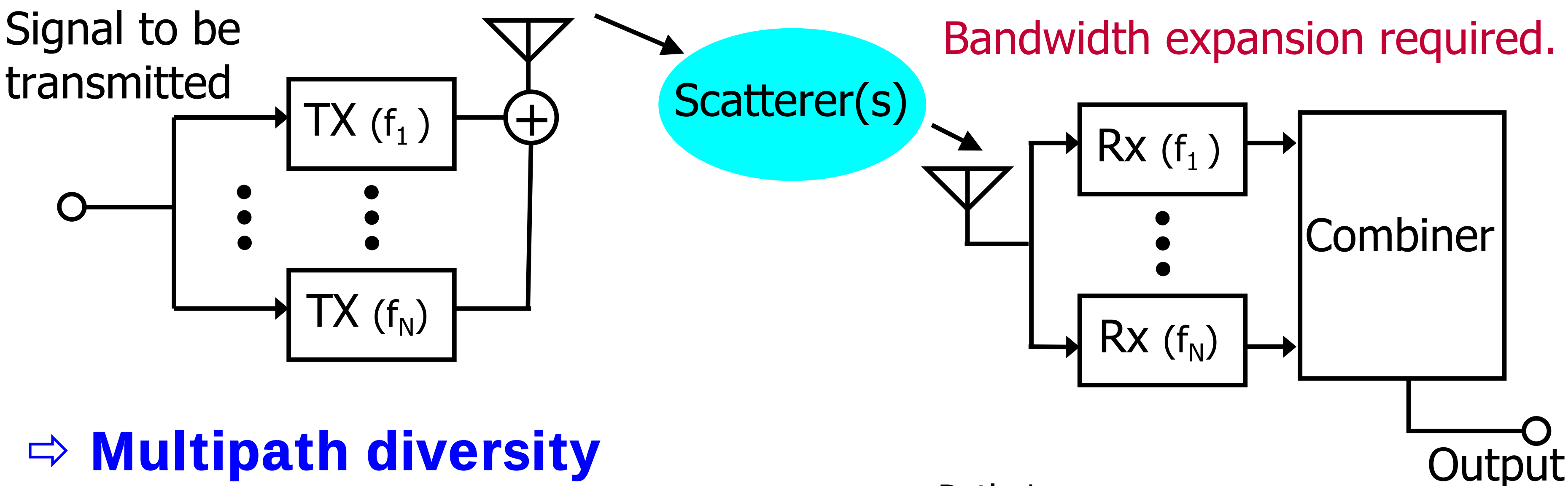
- Time diversity
- Frequency diversity
  - multicarrier communications
  - multipath diversity in spread spectrum communications.
- Spatial diversity
  - antenna diversity
  - macroscopic diversity via soft handovers
- Polarization diversity

Time Diversity

- Repetition after time delays.
- Usually achieved by coding and interleaving.

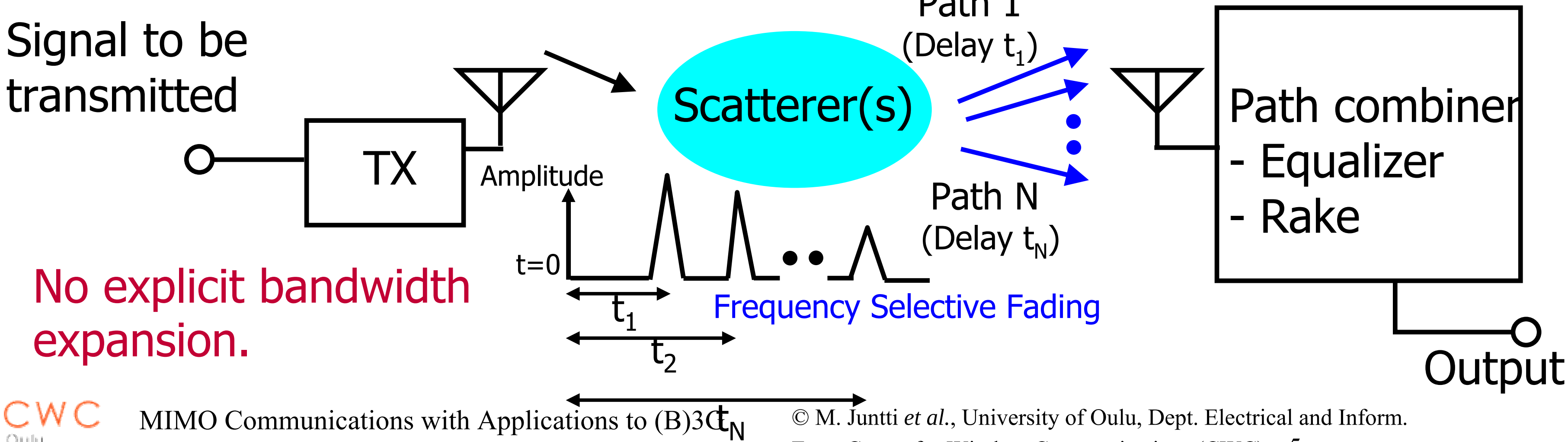


Frequency Diversity



Bandwidth expansion required.

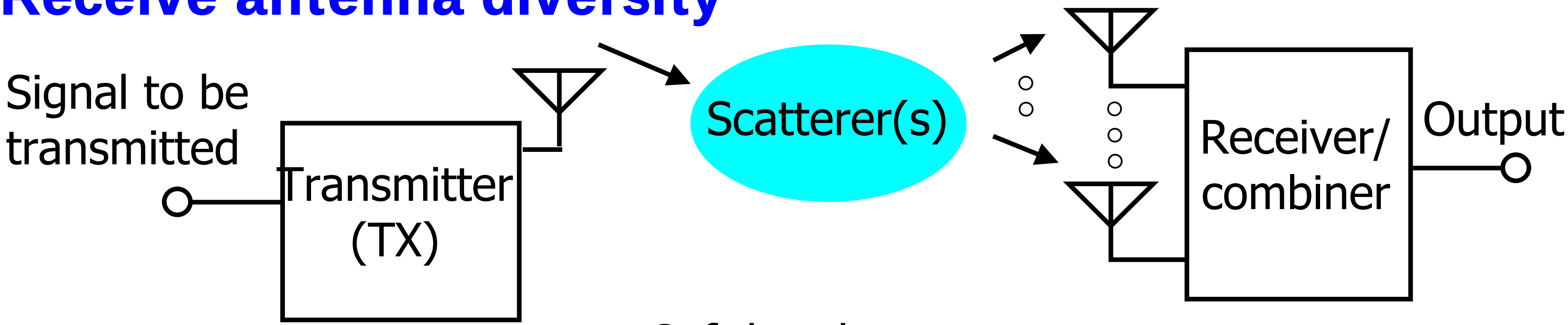
⇨ **Multipath diversity**



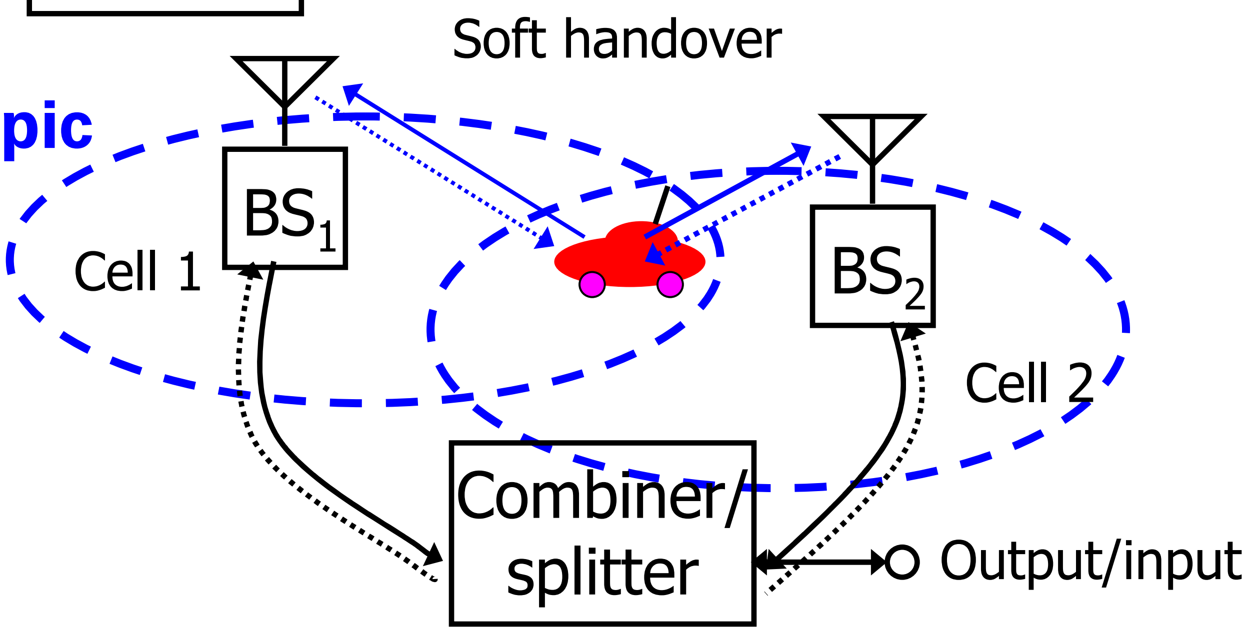
No explicit bandwidth expansion.

Space Diversity

Receive antenna diversity



Macroscopic diversity



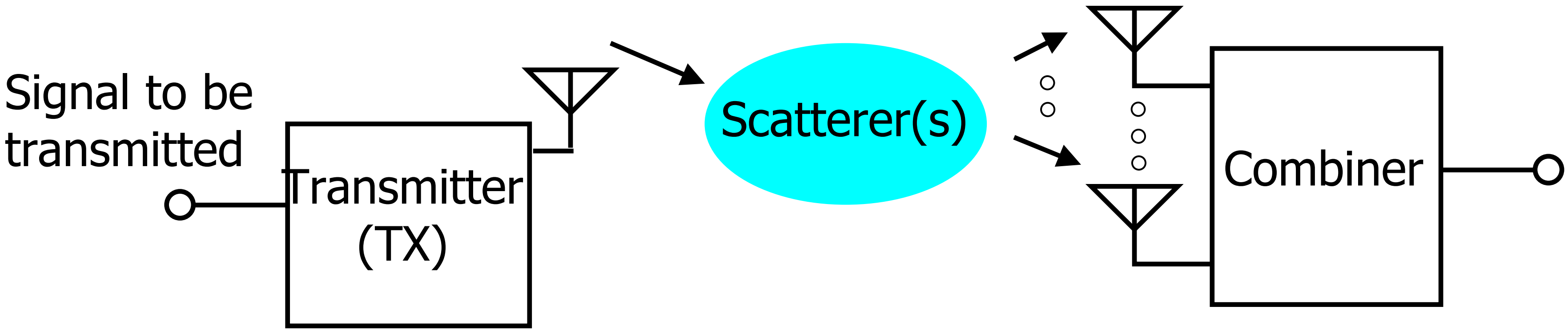
Capacity Implications

- Does diversity increase capacity?
- Ergodic capacity: $C = \max_{p(x)} I(X;Y)$, $P_{e,\max} \to 0, \text{as } n \to \infty$.
  - Codeword length → ∞ ⇨ infinite time-diversity.
  - ⇨ Diversity cannot increase the ergodic capacity.
  - However, it can improve the error performance or *error exponent*.
- Outage capacity is improved by diversity, since the diversity decreases the probability of outage.

2. Receive Diversity

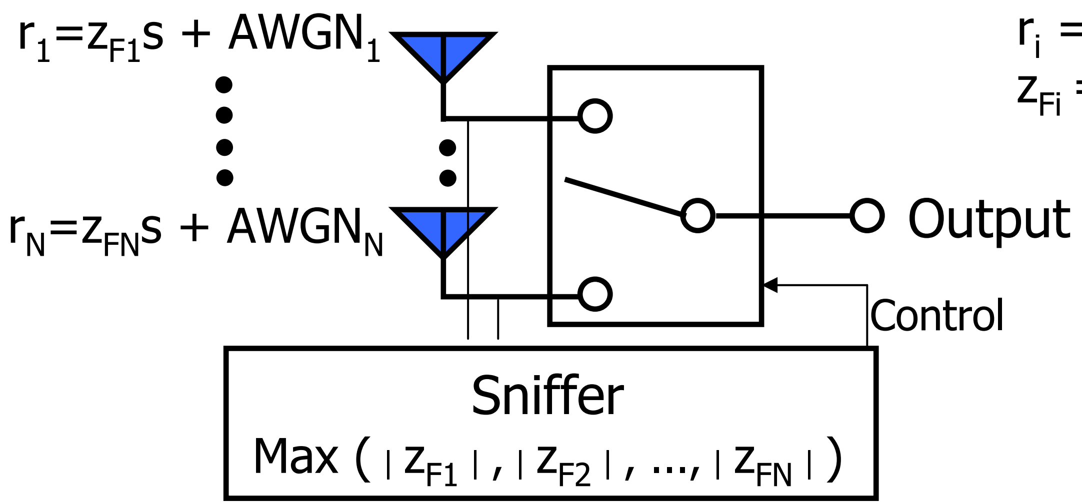
- Receive diversity: several independent observations of the signal (one data bit) are combined at the receiver.
  - Applicable to all diversity domains:
    - time
    - frequency
    - space.
- Combining techniques:
  - selection combining (SC)
  - equal gain combining (EGC)
  - maximum ratio combining (MRC).

Receive Antenna Diversity



- Collects more energy ⇨ *antenna gain*.
  - Independent noise and/or interference processes in different antennae ⇨ signal–to–noise ratio (SNR) and/or signal–to–interference–plus–noise ratio (SINR) gain.
- Observes several independent fading processes ⇨ *diversity gain*.

Selection Combining



s = transmitted signal
r_i = received signal on the i-th branch
z_{Fi} = fading complex envelope on the i-th branch

PDF of instantaneuos SNR:

Select the best availabale signal.

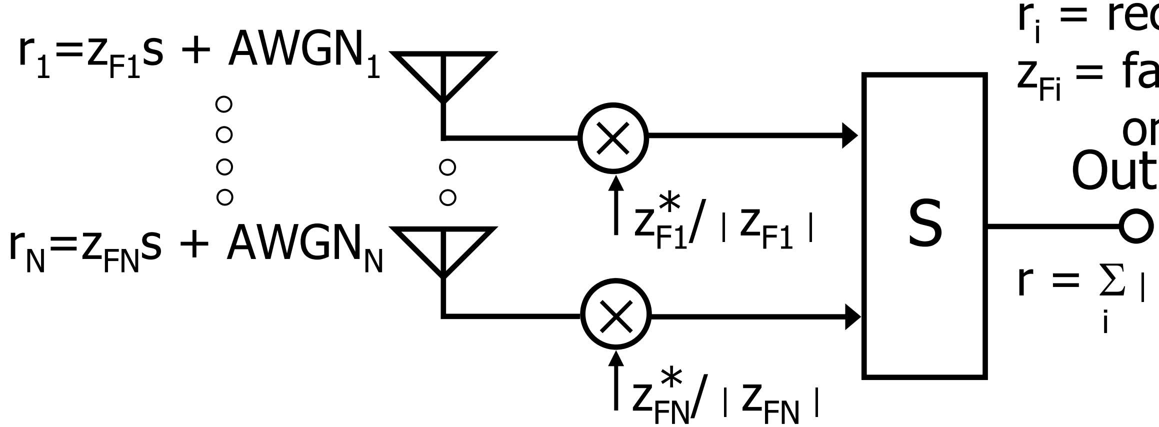
$$p(\gamma) = \frac{M}{\Gamma} \exp\left(-\frac{\gamma}{\Gamma}\right)\left\{1 - \exp\left(-\frac{\gamma}{\Gamma}\right)\right\}^{M-1}.$$

Equal Gain Combining

s = transmitted signal

r_i = received signal on the i-th branch

z_{Fi} = fading complex envelope on the i-th branch



$$r = \sum_i |z_{Fi}| s + \sum_i z^*_{Fi} / |z_{Fi}| AWGN_i$$

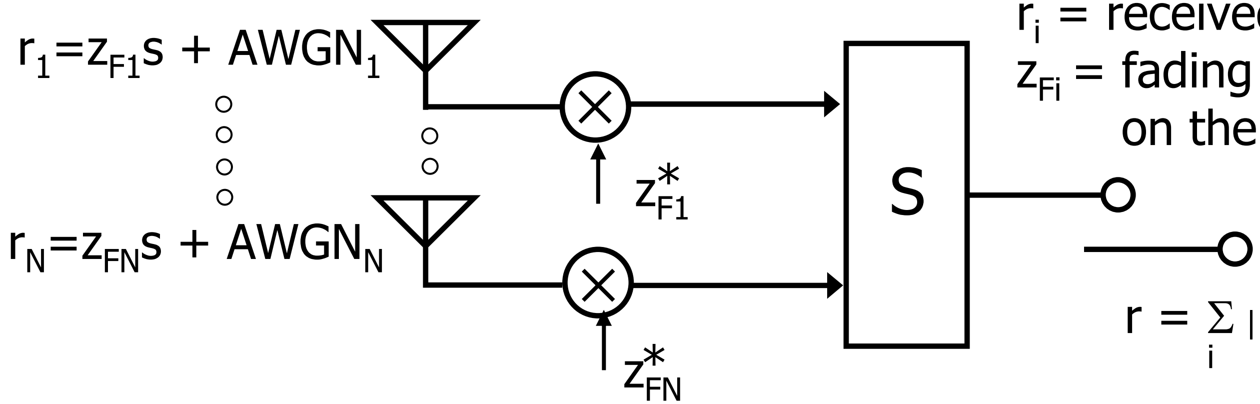
Phase rotation (carrier synchronization) and summing.

PDF of instantaneuos SNR (closed form not known, approximation):

$$p(\gamma) = \frac{2^{M-1} M^M}{(2M-1)!} \frac{\gamma^{M-1}}{\Gamma^M}$$

Maximum Ratio Combining

s = transmitted signal
r_i = received signal on the i-th branch
z_{Fi} = fading complex envelope on the i-th branch



$$r = \sum_i |z_{Fi}|^2 s + \sum_i z^*_{Fi} AWGN_i$$

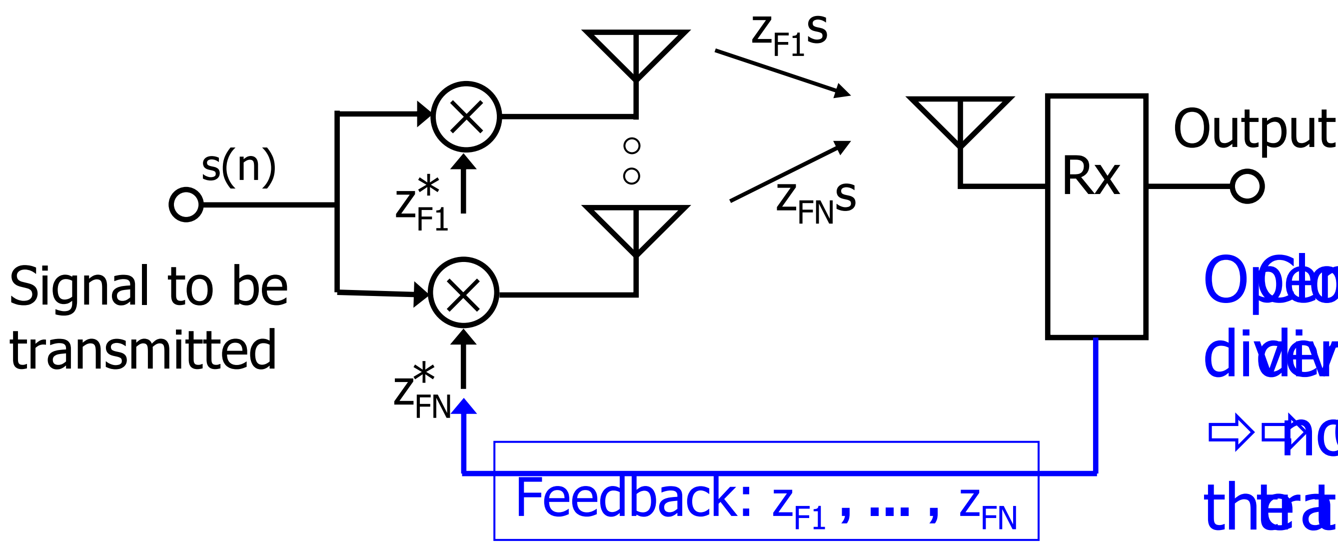
Phase rotation and weighting before summing ⇨ SNR maximization ⇨ optimal in Gaussian noise.

PDF of instantaneuos SNR:

$$p(\gamma) = \frac{1}{(M-1)!} \frac{\gamma^{M-1}}{\Gamma^{M}} \exp\left(-\frac{\gamma}{\Gamma}\right)$$

3. Transmit Diversity and Space–Time Coding

- Transmit diversity: one data bit is transmitted via several independent (spatial) channels.
  - The conventional diversity techniques in time and frequency domains could be classified also to this class.
- No bandwidth expansion.



Open-loop TX diversity ⇨ no CSI at the transmitter

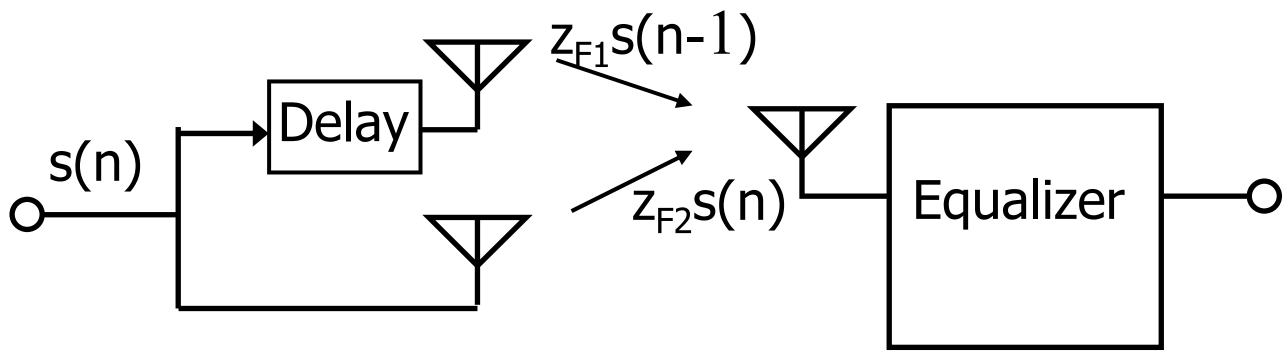
Closed-loop TX diversity ⇨ CSI at the transmitter

Early Solutions: Delay and Waveform Diversity

Delay diversity

- No BW expansion.
- Frequency–flat → frequency–selective.

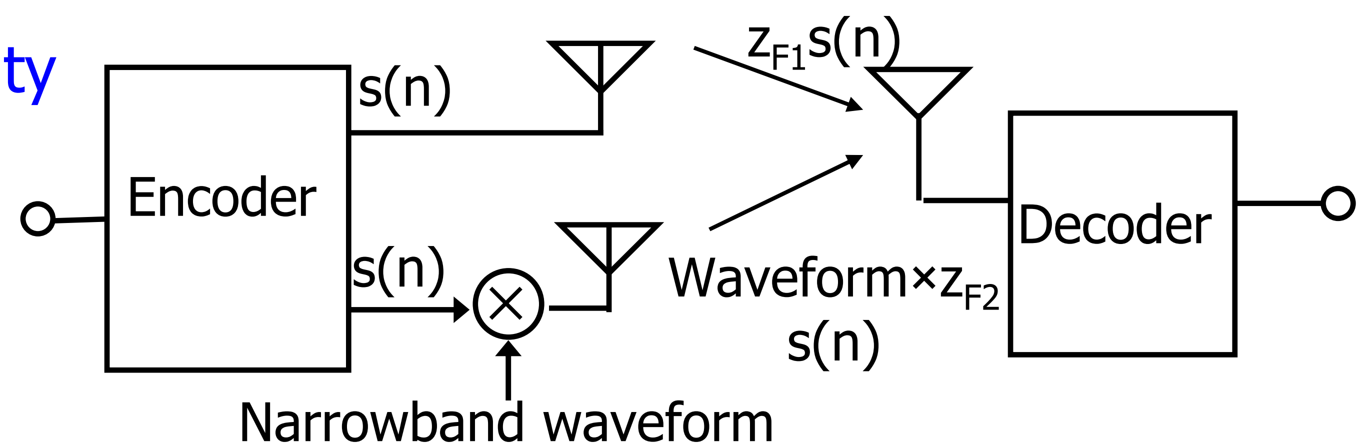
⇨ Spatial diversity into ”path” diversity .



Waveform diversity

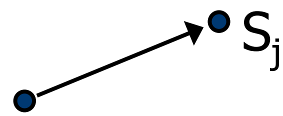
- BW expansion.
- slow → fast.

⇨ Spatial diversity into ”path” diversity.



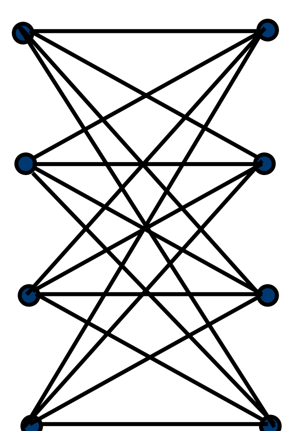
Trellis Representation of Delay Diversity

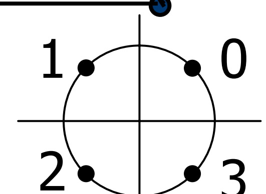
S_i: X_0Y_0 X_1Y_1 X_2Y_2 X_3Y_3



If current state is S_i, the input symbol is "j", (j = 0 ... 3)
⇨Antenna #1 transmits X_j and antenna #2 transmits Y_j, and the next state is S_j.

S_0	00	01	02	03
S_1	10	11	12	13
S_2	20	21	22	23
S_3	30	31	32	33



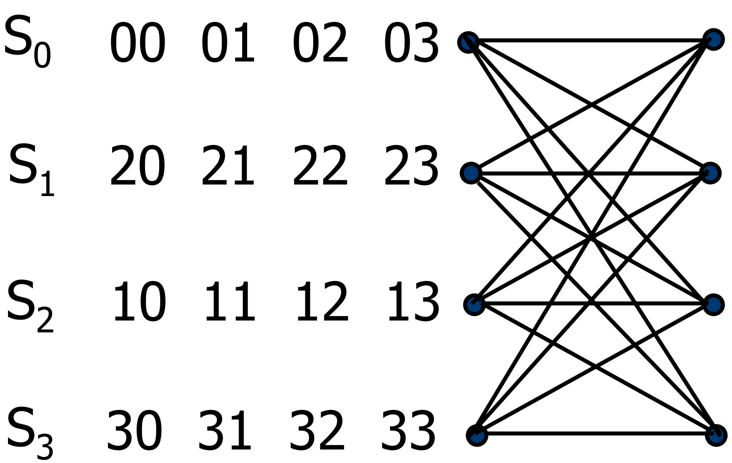


Example: The current state is S_0, and the input sequence is (10, 01, 11, 00, 01, ...). The corresponding QPSK symbol sequence is (2, 1, 3, 0, 1, ...).
⇨ The transmitted symbol sequences in delay diversity:

Antenna 1: 0, 2, 1, 3, 0, 1, ...
Antenna 2: 2, 1, 3, 0, 1, ...

Space–Time Trellis Codes

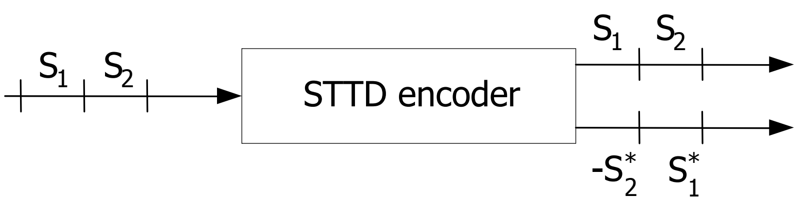
Allow more general and flexibe allocation of transmitted sequences ⇨space–time trellis codes (STTrC).



Example: The input sequence is (10, 01, 11, 00, 01, ...) → QPSK symbol sequence (2, 1, 3, 0, 1, ...).
⇨ The transmitted symbol sequences in delay diversity:

Antenna 1: 0, 1, 2, 3, 0, 1, ...
Antenna 2: 2, 1, 3, 0, 1, ...

Alamouti scheme (2×2 Space–Time Block Coding)



$$r_j^1 = a_j^1 s_1 - a_j^2 s_2^* + n_j^1$$
$$r_j^2 = a_j^1 s_2 + a_j^2 s_1^* + n_j^2$$

$$s_1 = \sum_{j=1}^{L} r_j^1 a_j^{1*} + r_j^{2*} a_j^2$$
$$s_2 = \sum_{j=1}^{L} - r_j^{1*} a_j^2 + r_j^2 a_j^{1*}$$

2×2 space–time block coding (STBC) = Alamouti scheme

- No BW expansion.
- Simple MRC at the receiver.
- Open–loop method.

Space–Time Block Coding

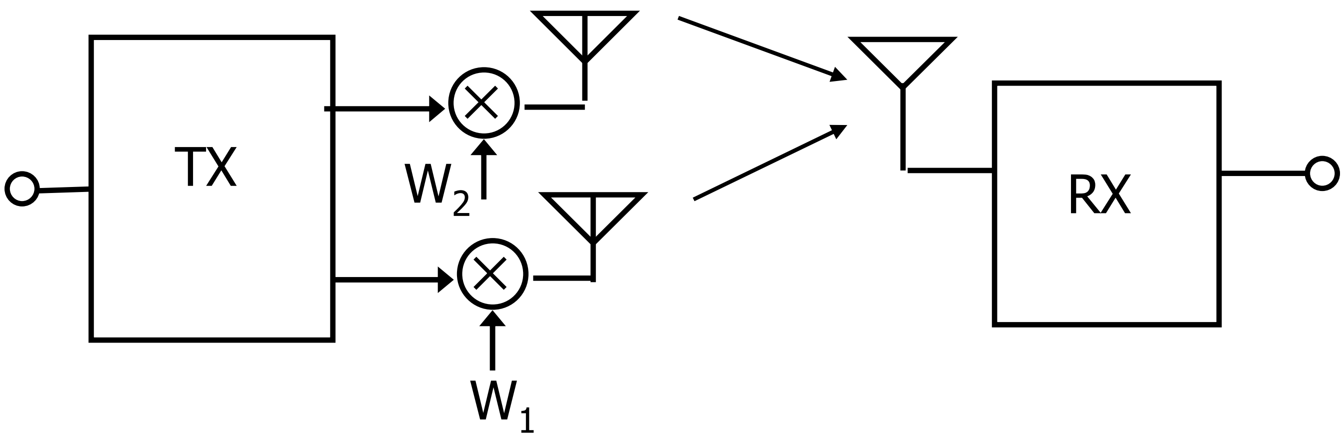
STBC can be generalized to arbitrary numbers of TX and RX antennae.

- No optimal unique code design exists.
- Both real and complex designs exist.
- An example code:

$$(s_1, s_2, s_3, s_4) \longrightarrow \begin{bmatrix} (s_1, & -s_2, & -s_3, & -s_4, & s_1^*, & -s_2^*, & -s_3^*, & -s_4^*) \\ (s_2, & s_1, & s_4, & -s_3, & s_2^*, & s_1^*, & s_4^*, & -s_3^*) \\ (s_3, & -s_4, & s_1, & s_2, & s_3^*, & -s_4^*, & s_1^*, & s_2^*) \\ (s_4, & s_3, & -s_2, & s_1, & s_4^*, & s_3^*, & -s_2^*, & s_1^*) \end{bmatrix}$$

Closed–Loop Schemes

- Use transmitter channel state information (CSI) to weigh the transmission to optimize performance.
  - Typically SINR maximization in the receiver.
- Usually imperfect TX-CSI.
  - Often quantized feedback from RX to TX.



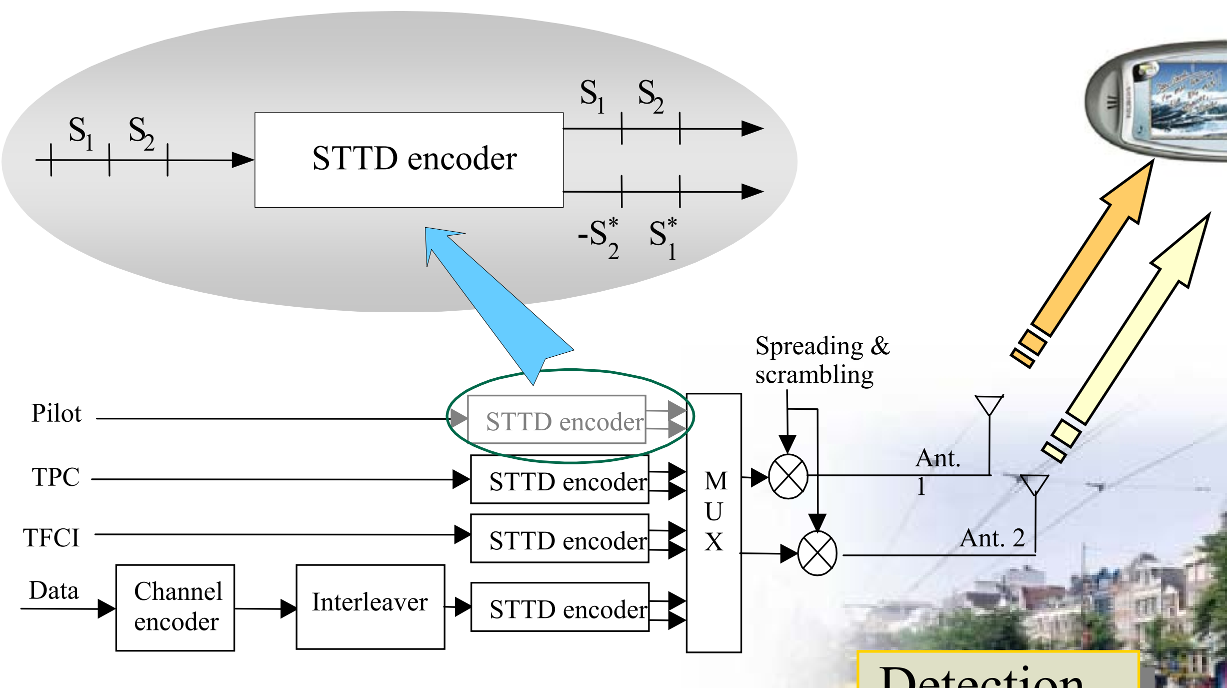
4. Transmit diversity in 3G systems

- Applied due to the fact that UE has only 1 antenna
  - Robustness against fading
- Open loop mode, STTD (Alamouti scheme)
- Closed loop modes 1 & 2
- Time-switched TX diversity applied to sync. channel

Open Loop Transmit Diversity, STTD

- **Space-Time (Block Coded) Transmit Diversity (STTD) for WCDMA**
  - **space-time coding over two symbols**
    - **➔ simple detection at the terminal**
- **Can be used in all physical channels except in SCH**

Rx signals for time instants 1 & 2,
j = path index
α = channel coeff.

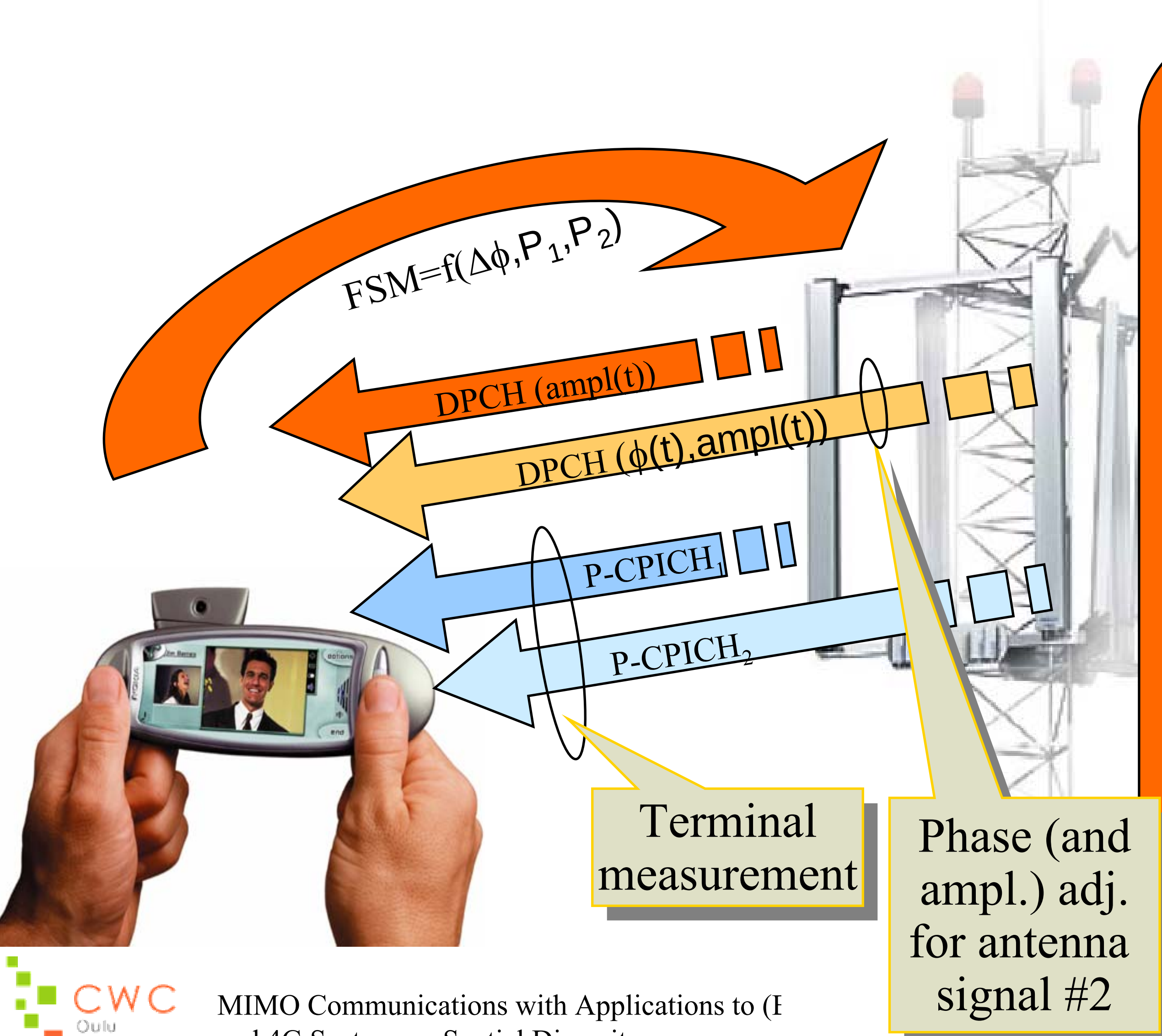


$$r_j^1 = \alpha_j^1 S_1 - \alpha_j^2 S_2^* + n_j^1$$
$$r_j^2 = \alpha_j^1 S_2 + \alpha_j^2 S_1^* + n_j^2$$

$$S_1 = \sum_{j=1}^{L} r_j^1 \alpha_j^{1^*} + r_j^{2^*} \alpha_j^2$$
$$S_2 = \sum_{j=1}^{L} -r_j^{1^*} \alpha_j^2 + r_j^2 \alpha_j^{1^*}$$

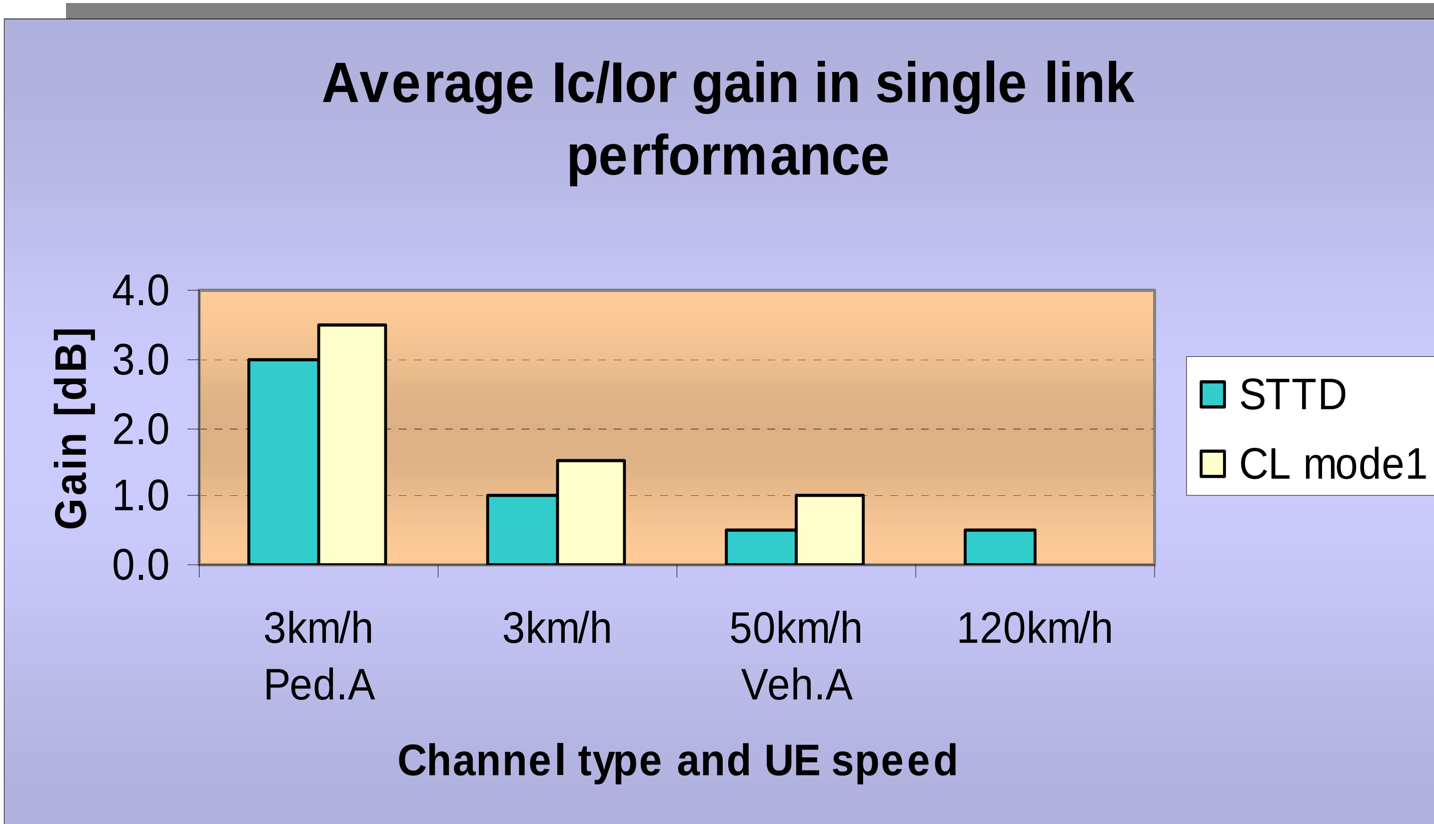
Detection at terminal, integration over L paths

Closed Loop Transmit Diversity Modes



- UE measures relative phase (and power) of two pilot (Primary CPICH) signals
- UE sends adjustment command to BS, feedback signaling message (FSM)
- FSM applied on DPCH to antenna signal #2 phasing, and (mode2 only) amplitude weighting (0.2/0.8) for both antenna signals

Link performance: Average Tx diversity gain



Gain in relative Tx power (Ic/Ior) = user/total Tx power, G = 3dB

Average = through different data rates (12.2 - 144kbps)

5. Summary and Conclusions

- Diversity has to be applied in one form or another
- Receive diversity desirable vs. TX diversity
- Channel state information (CSI) very beneficial
- Multi-user diversity employing CSI can be achieved through scheduling (e.g. HSDPA in 3GPP)

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