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Power-Efficient Opportunistic Amplify-and-Forward Single-Relay Aided Multi-User SC-FDMA Uplink

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Outline

- ☐ The state-of-art
- ☐ Relay assisted SC-FDMA system model
- ☐ Signal detection at the BS and results
- ☐ Opportunistic cooperative relaying and results
- ☐ Conclusions

Key References

- ❏ N. Benvenuto and R. Dinis and D. Falconer and S. Tomasin, “Single Carrier Modulation With Nonlinear Frequency Domain Equalization: An Idea Whose Time Has Come–Again”, *Proceedings of the IEEE*, vol. 98, no. 1, pp. 69–96, Jan. 2010.
- ❏ J. Zhang, L.-L. Yang and L. Hanzo, “Multi-user performance of the amplify-and-forward single-relay assisted SC-FDMA uplink”, *in Proceedings of IEEE VTC2009-Fall*, 2009.
- ❏ L.-L. Yang, *Multicarrier Communications*, Wiley, 2009.
- ❏ H. G. Myung and J. Lim and D. J. Goodman, “Single carrier FDMA for uplink wireless transmission”, *IEEE Vehicular Technology Magazine*, pp. 30–38, Sept. 2006.
- ❏ A. Bletsas, A. Khisti, D. P. Reed and A. Lippman, “A simple cooperative diversity method based on network path selection”, IEEE Journal on Selected Areas in Commuications, vol. 24, no. 3, pp. 659–672, Mar. 2006.
- ❏ A. Sendonaris, E. Erikip and B. Aazhang, “User cooperative diversity - part I and II”, *IEEE Transactions on Communications*, vol. 51, pp. 1927–1948, Nov. 2003.
- ❏ D. Falconer, S. L. Ariyavisitakul, A. Benyamin-Seeyar and B. Eidson, “Frequency domain equalization for single-carrier broadband wireless systems”, *IEEE Communications Magazine*, pp. 58–66, Apr. 2002.

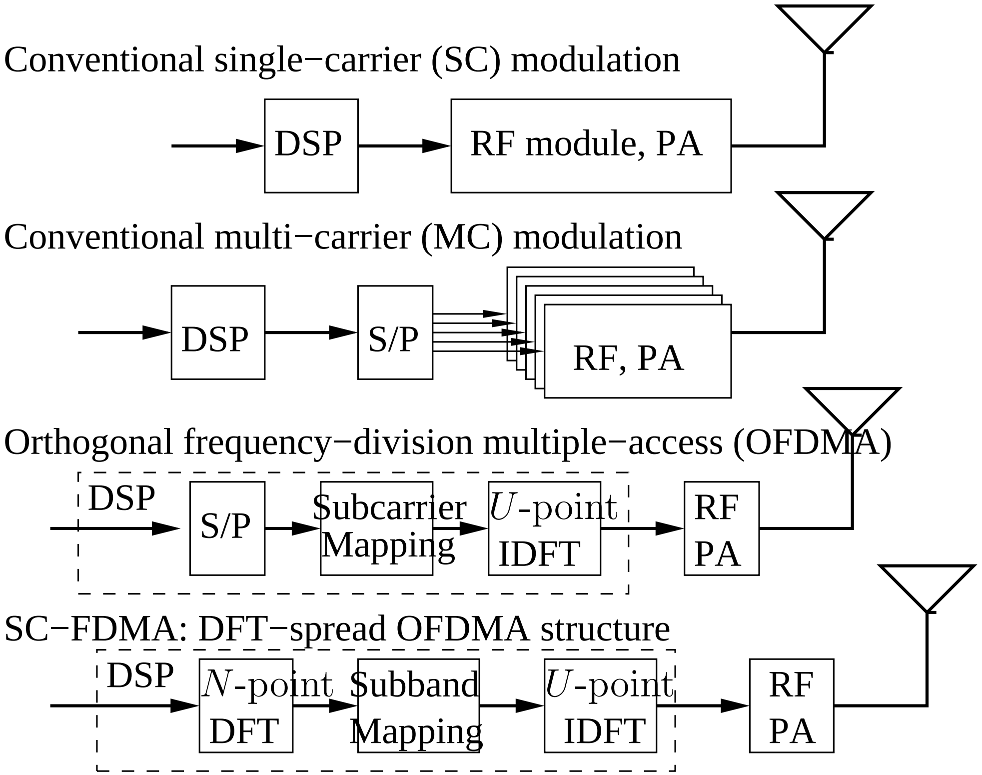
Motivation

- 3GPP LTE-Advanced prospective
- Green radio awareness - power efficiency
- High transmission throughput requirement: broadband rather than narrowband
- Problem: have to mitigate both the shadow and Rayleigh/Rician fading over dispersive channels

Why SC-FDMA?

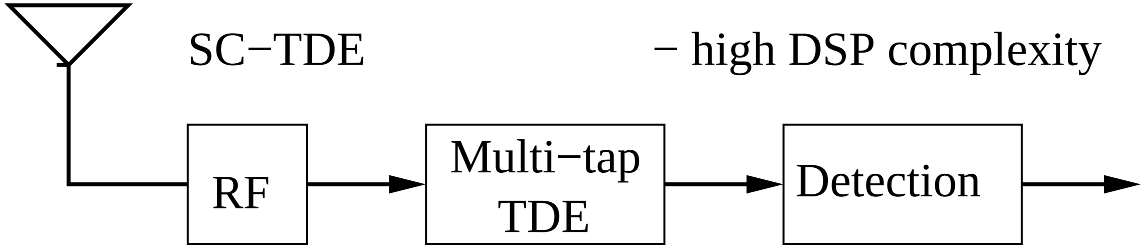
❑ Carrier modulation aware transmitter design

- Power amplifier (PA) requires *low peak-to-average power ratio (PAPR)* due to its limited linear range

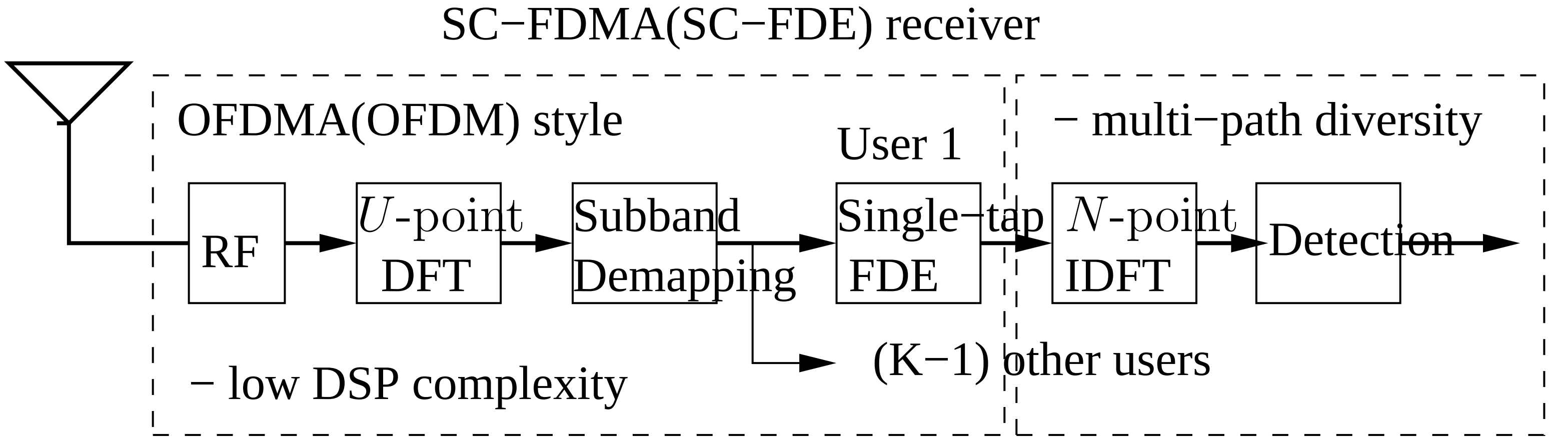


Signal generation	RF module and PA	PAPR	Hardware complexity	Configure flexibility	Multi−path diversity
Time −domain (TD)	Single	Low	Low	Constant −moudulus modulation	Depend on receiver
TD	Multiple	Low	High	Constant −moudulus modulation	No
Frequency −domain (FD)	Single	High	Low	Flexible Reconfig	No
TD	Single	Low	Low	Flexible Reconfig	Yes

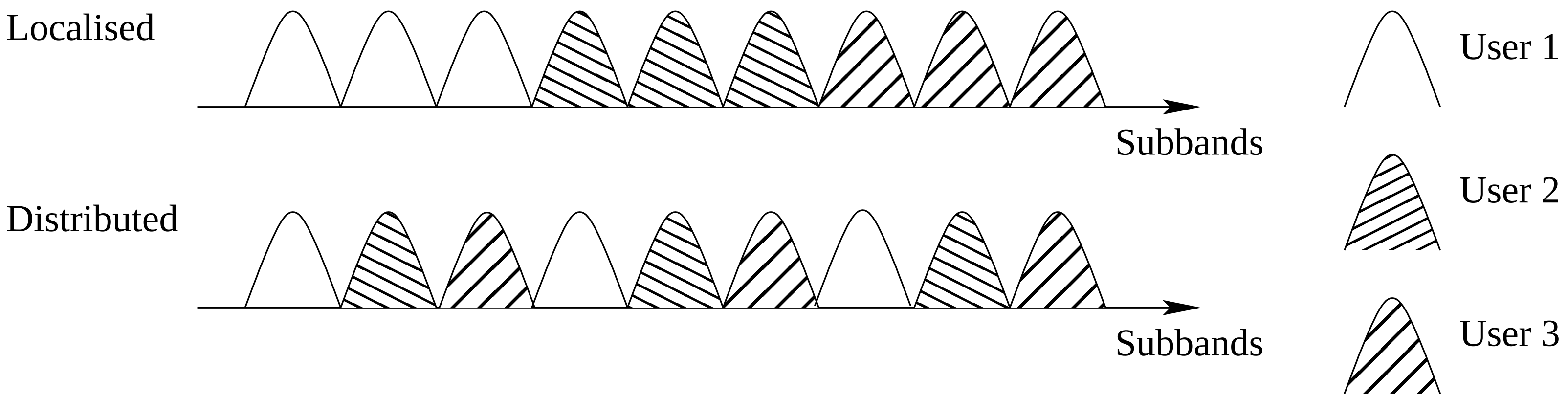
- Digital signal processing (DSP) at receiver
  - Conventional SC receiver: *time-domain equaliser (TDE) with hundreds of filter taps in case of long channel impulse responses imposed by frequency-selective fading*



  - SC-FDE receiver *transforms the received signal to the frequency-domain, as in OFDM and employs single-tap multiplicative frequency-domain equaliser (FDE)*
  - SC-FDE receiver *includes IDFT operation after conventional OFDM receiver*



❑ Multiple-access oriented subband mapping schemes



- Distributed mode provides higher *multi-path diversity* gain than localised mode.
- Localised mode may achieve *multi-user diversity* when invoking *channel-dependent scheduling*, it is more suitable for a system in which a few users require high bit-rate.
- Interleaved mode is a special case of the distributed mode, where subbands are arranged equidistantly from each other.
- The transmitted TD signal of localised mode requires *a few subcarriers*, while for interleaved mode only *single carrier* is used.

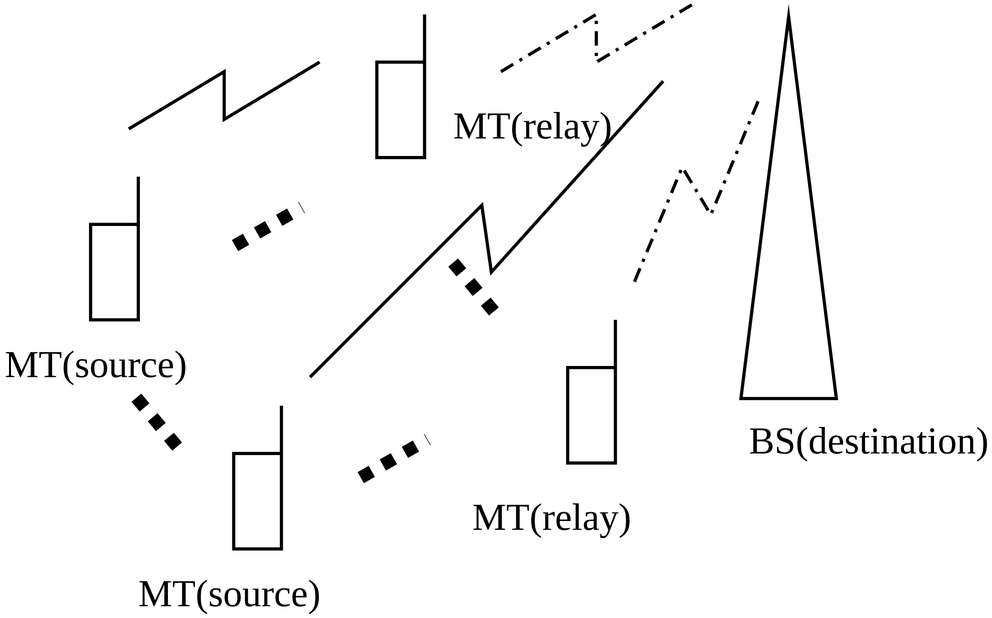
Why Cooperation?

- ❏ Aims
  - Achieving energy/power efficiency
  - Increasing system throughput
  - Extending cellular coverage
  - Supports multiple users
  - Guarantees a given quality of service (QoS)
- ❏ Relay selection: whom to cooperate with?
  - Fixed - *aiming for cooperative diversity, fixed relaying gain*
  - Random - *limited relaying gain and selection diversity gain*
  - Distance-dependent - *aiming for relaying gain*
  - Channel-dependent - *aiming for both relaying and selection diversity gains* - **Opportunistic Relaying**

Opportunistic Amplify-and-Forward Cooperative Relaying for SC-FDMA Uplink

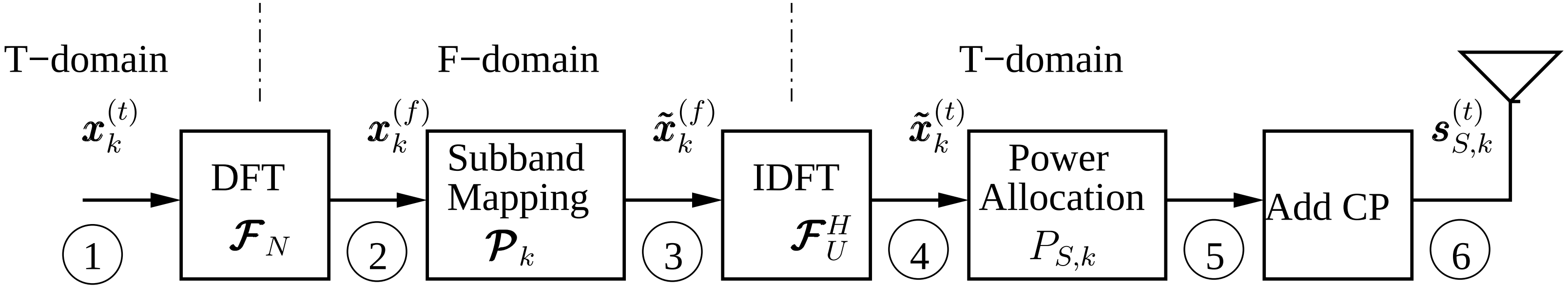
❑ Our proposed systems are capable of providing:
  - Multi-user (selection) diversity gain
  - Cooperative (spatial) diversity gain
  - Multi-path (frequency) diversity gain

❑ Additionally,
  - Free of multi-user interference (MUI) and reduced AF relaying noise
  - Low DSP complexity at the relay and BS



Source MT Transmitter

❑ DFT-spread-OFDMA style transmitter



- k-th user's N consecutive TD symbol in the vector $\boldsymbol{x}_k^{(t)}$
- Bandwidth (BW) expansion factor M supports a maximum of M users
- N-point FFT matrix $\boldsymbol{\mathcal{F}}_N$ offers a normalised BW of N per user
- U-point IFFT matrix $\boldsymbol{\mathcal{F}}_U^H$ provides the total normalised BW of $U = N \times M$

Slide 10 - Relay Assisted SC-FDMA System Model

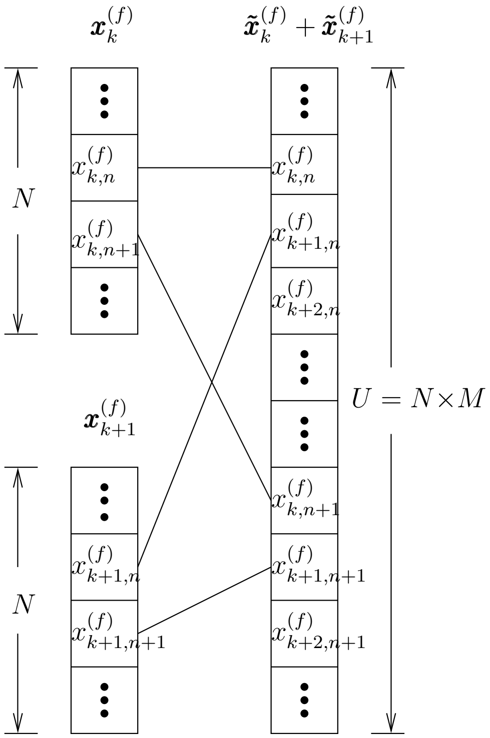
- Total transmitted signal power P_t is normalised to unity,
  the source MT's transmitted power $P_{St,k} = \epsilon_{S,k}\alpha_{S,k}P_t$,
  power sharing factor $\alpha_{S,k} = \alpha_{R,k} = 0.5$, in terms of Equal Power Allocation (EPA),
  Power Control Error (PCE): log-normal distributed samples with zero mean and variance of σ_ϵ^2, i.e. $\epsilon_{S,k}(dB) \sim \mathcal{N}(0, \sigma_\epsilon^2)$.

- Subband mapping matrix $\boldsymbol{\mathcal{P}}_k$ of the k-th user
  - Interleaved mode - *achieves multi-path diversity gain*

$$\mathcal{P}_{k,un} = \begin{cases} 1, & \text{for } u = nM + k \\ 0, & \text{otherwise} \end{cases}$$

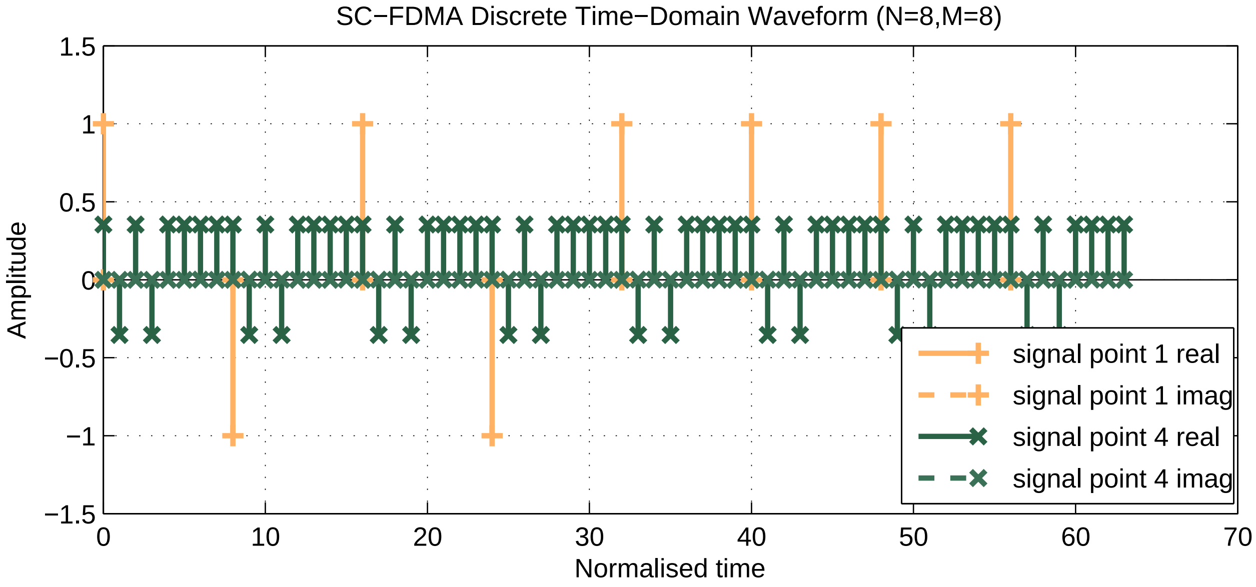
- Transmitted signal before inserting cyclic-prefix CP

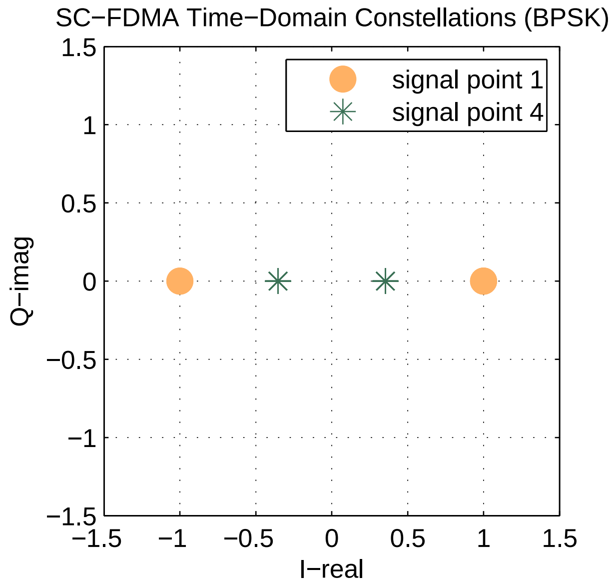
$$\boldsymbol{s}_{S,k}^{(t)} = \sqrt{P_{St,k}}\boldsymbol{\mathcal{F}}_U^H\boldsymbol{\mathcal{P}}_k\boldsymbol{\mathcal{F}}_N\boldsymbol{x}_k^{(t)}$$

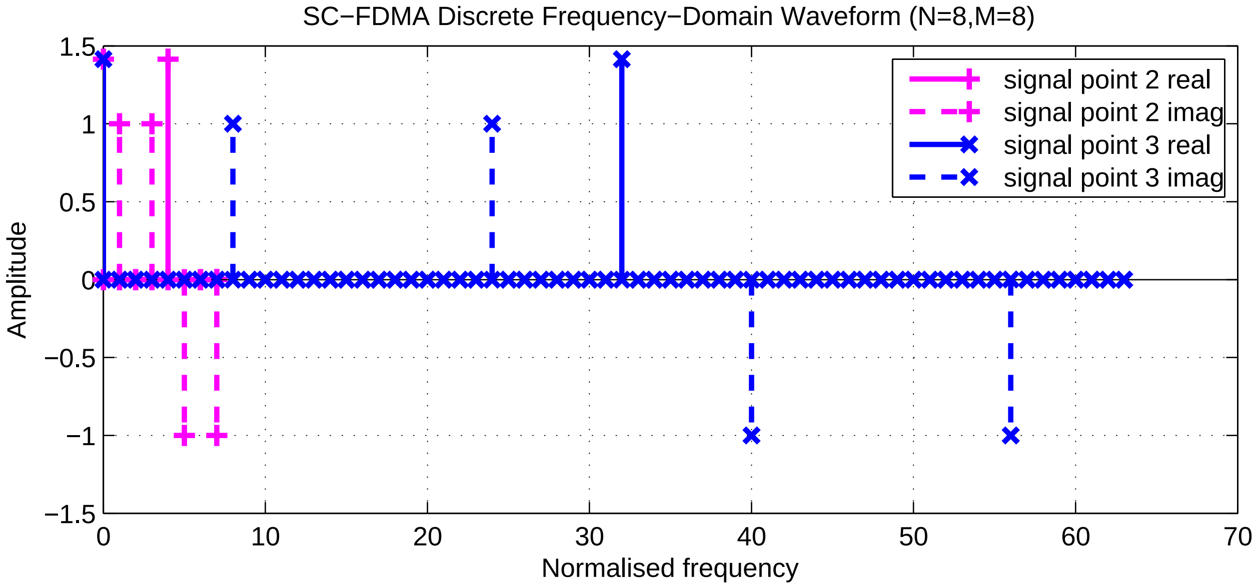


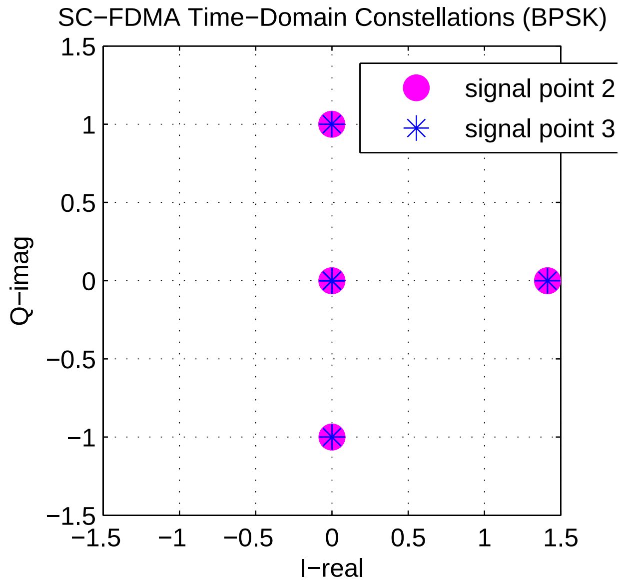
Interleaved subband mapping

Slide 11 - Relay Assisted SC-FDMA System Model


SC−FDMA Discrete Time−Domain Waveform (N=8,M=8)

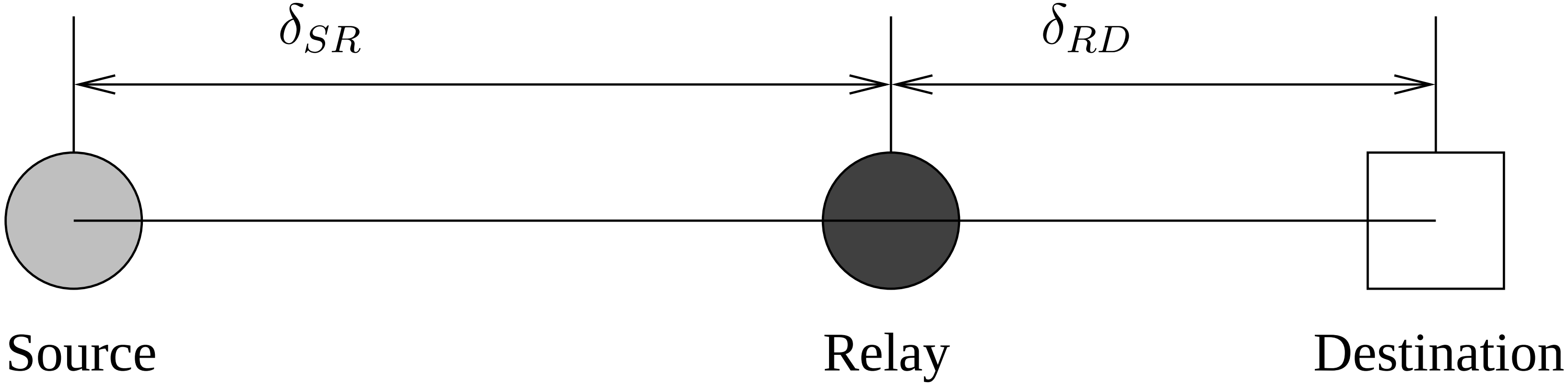

SC−FDMA Time−Domain Constellations (BPSK)


SC−FDMA Discrete Frequency−Domain Waveform (N=8,M=8)


SC−FDMA Time−Domain Constellations (BPSK)

Channel Modelling

- ❏ 2D propagation map, direct link: source-destination (S-D), relaying links: source-relay (S-R), relay-destination (R-D)
- ❏ Reference distance: S-D link, normalised distances: $\delta_{SR} + \delta_{RD} = 1$
- ❏ Average path-loss: $\delta_{SR}^{-\eta}$ and $\delta_{RD}^{-\eta}$
- ❏ Path-loss exponent $\eta = 4$, shadow fading $\xi(dB) \sim \mathcal{N}(0, \sigma_\xi^2)$
- ❏ Instantaneous path-loss: $G_{SR} = \xi_{SR}\delta_{SR}^{-\eta}$ and $G_{RD} = \xi_{RD}\delta_{RD}^{-\eta}$



Assumptions

- BPSK modulation without channel coding
- AWGN $\mathcal{CN}(0, \sigma_N^2)$ at the relay and BS
- Perfect Channel State Information at the Receiver (CSIR) of the BS
- Channel-Dependent Relay Selection (CD-RS) based on pilots
- Orthogonal subbands of the DFT-S-OFDM signals, avoiding MUI among the source MT
- A sufficiently long CP for each transmitted TD signal block, leading to zero inter-block interference (IBI)
- Each subband encounters independent and identically Rayleigh distributed block fading
- The K users' signals are transmitted synchronously over the uplink channels

Relaying Topologies

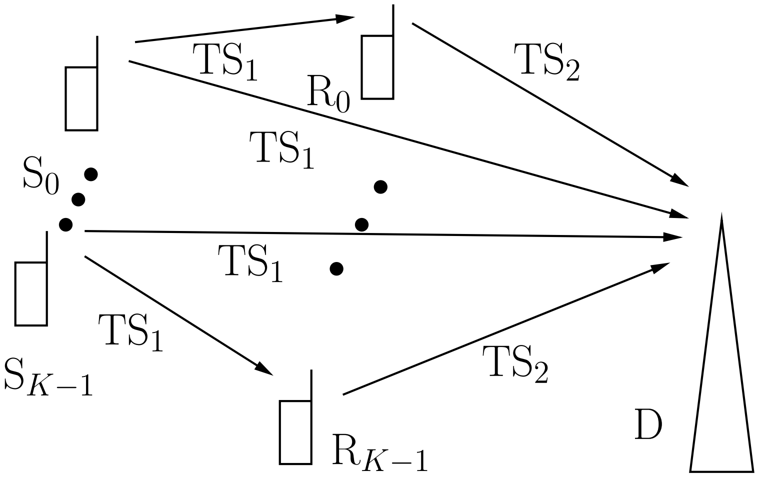
- Half-Duplex Time-Division Cooperation
  - Time slots
    TS_1: S→D and S→R, TS_2: R→D
  - Direct Transmission

$$\boldsymbol{r}_{SD}^{(t)} = \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{SD,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}$$

  - Single-Dedicated-Relaying (SDR):
    K sources and K relays

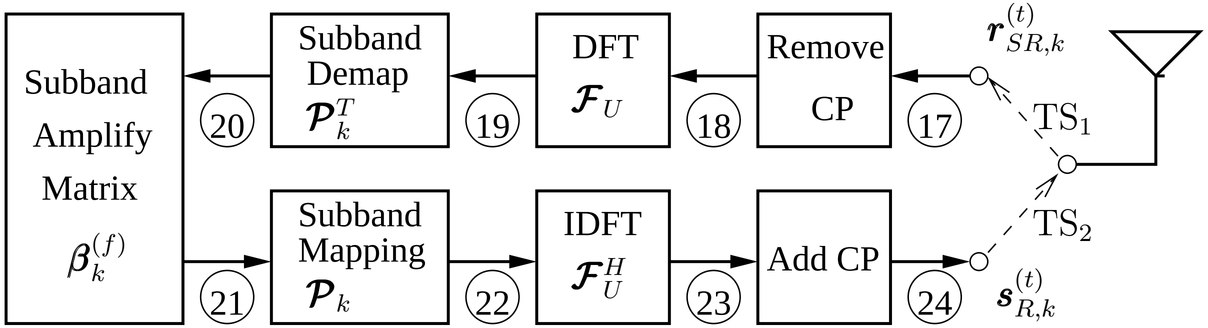
$$\boldsymbol{r}_{SR,k'}^{(t)} = \sqrt{G_{SR}} \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{SR,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{R,k}^{(t)}$$

$$\boldsymbol{r}_{RD}^{(t)} = \sqrt{G_{RD}} \sum_{k'=0}^{K-1} \tilde{\boldsymbol{H}}_{RD,k'}^{(t)} \boldsymbol{s}_{R,k'}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}$$



Cooperative Strategies

- ❑ Amplify-and-Forward combined with subband-based FD equalisation and remapping



  - Subband-specific equalisation and amplification matrix

$$\boldsymbol{\beta}_k^{(f)} = \mathrm{diag}\{\beta_{k0}^{(f)}, \beta_{k1}^{(f)}, \cdots, \beta_{k(N-1)}^{(f)}\},$$

where the n-th element is the specific *gain factor* of the n-th subband

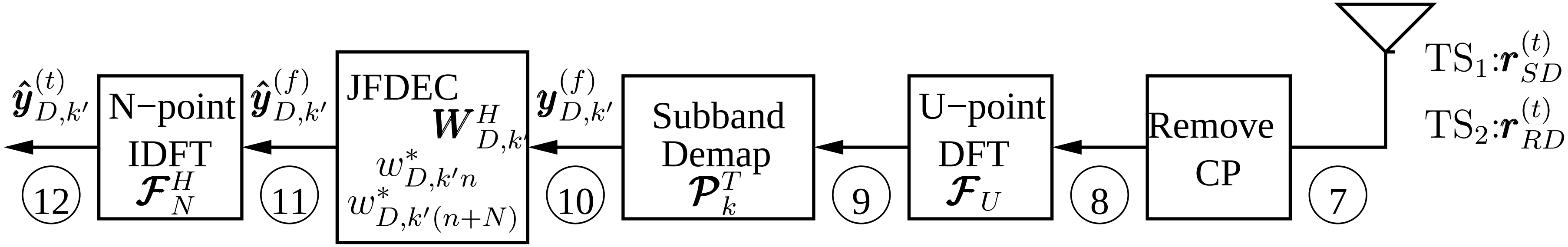
$$\beta_{kn}^{(f)} = \sqrt{P_{Rt,k}/[P_{St,k}G_{SR}|h_{SR,kn}^{(f)}|^2 + \sigma_N^2]}.$$

  - The transmitted signal of the k-th relay during TS$_2$

$$\boldsymbol{s}_{R,k}^{(t)} = \sqrt{P_{St,k}G_{SR}}\boldsymbol{\mathcal{F}}_U^H \boldsymbol{\mathcal{P}}_k \boldsymbol{\beta}_k^{(f)} \boldsymbol{H}_{SR,k}^{(f)} \boldsymbol{x}_k^{(f)} + \bar{\boldsymbol{n}}_{R,k}^{(t)}$$

Signal Processing at the BS's Receiver

❑ MMSE Assisted Joint FD Equalisation and Combining (JFDEC)



- The k'-th user's received signals include direct and relay branches:

$$\boldsymbol{y}^{(f)}_{D,k'} = \sqrt{P_{St,k'}}\boldsymbol{H}^{(f)}_{D,k'}\boldsymbol{x}^{(f)}_{k'} + \boldsymbol{n}^{(f)}_D$$

- MMSE optimum weight matrix $\boldsymbol{W}_{D,k'}$, jointly carry out single-tap FDE and diversity combining of the direct and relay branches.

Slide 17 - Single Detection at the BS

❑ JFDEC-MMSE cont.

- The n-th and $(n+N)$-th element of the JFDEC $\boldsymbol{W}_{D,k'}$ can be expressed as

$$w_{D,k'n} = \frac{h^{(f)}_{D0,k'n}}{\sigma_N^2}\left(\frac{|h^{(f)}_{D0,k'n}|^2}{\sigma_N^2} + \frac{|h^{(f)}_{D1,k'n}|^2}{\mathcal{N}_{D1,n}} + P^{-1}_{St,k'}\right)^{-1},$$

$$w_{D,k'(n+N)} = \frac{h^{(f)}_{D1,k'n}}{\mathcal{N}_{D1,n}}\left(\frac{|h^{(f)}_{D0,k'n}|^2}{\sigma_N^2} + \frac{|h^{(f)}_{D1,k'n}|^2}{\mathcal{N}_{D1,n}} + P^{-1}_{St,k'}\right)^{-1}$$

- TD decision variable vector

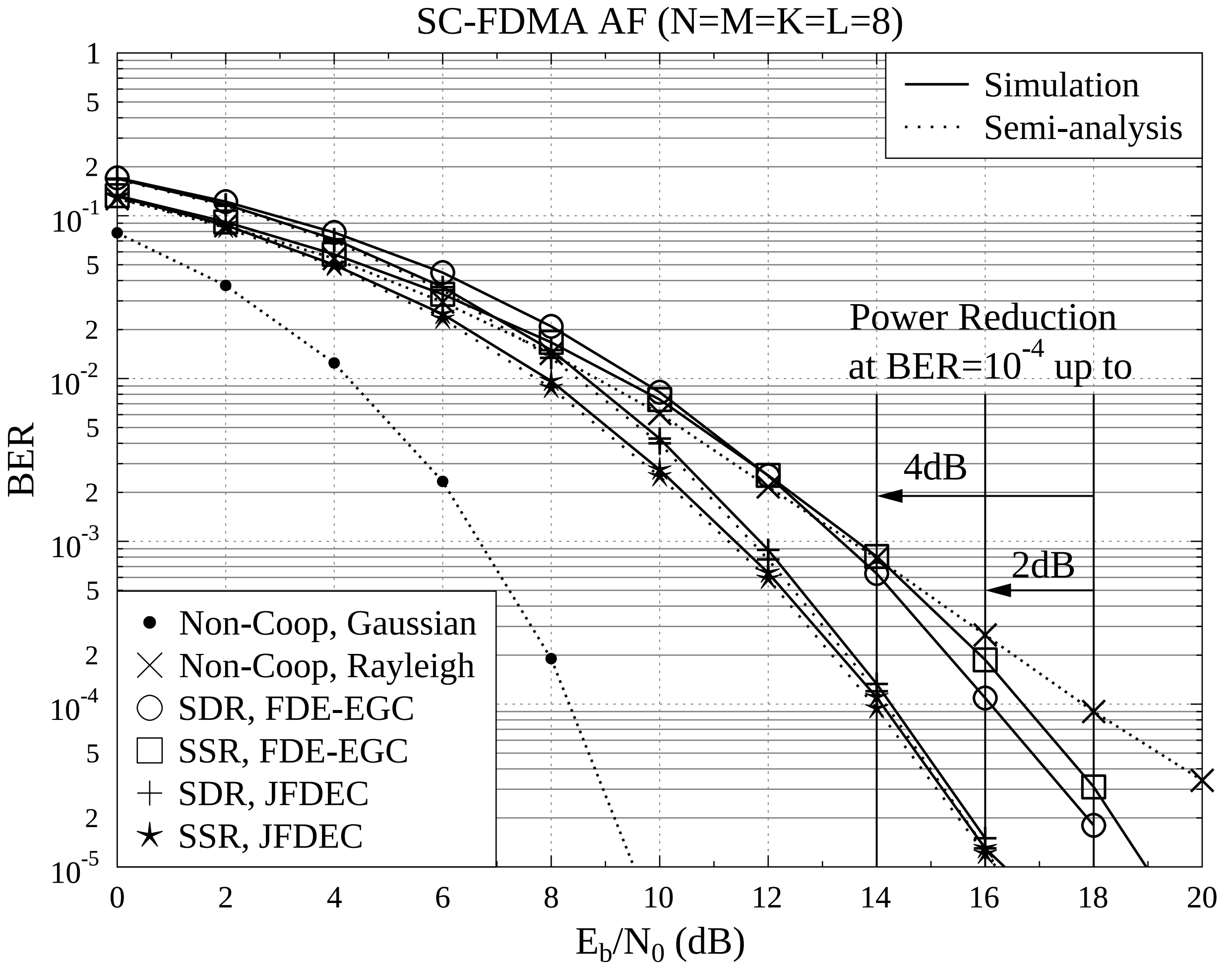
$$\hat{\boldsymbol{y}}^{(t)}_{D,k'} = \boldsymbol{\mathcal{F}}^H_N \boldsymbol{W}^H_{D,k'} \boldsymbol{y}^{(f)}_{D,k'}$$

- The k'-th user's overall received SINR

$$\gamma_{k'} = \left\{\frac{1}{N}\sum_{n=0}^{N-1}\left[\begin{array}{c} 1+\gamma_{SD,k'n}+ \\ \left(\gamma^{-1}_{SR,k'n}+\gamma^{-1}_{RD,k'n}\right)^{-1} \end{array}\right]^{-1}\right\}^{-1} - 1$$

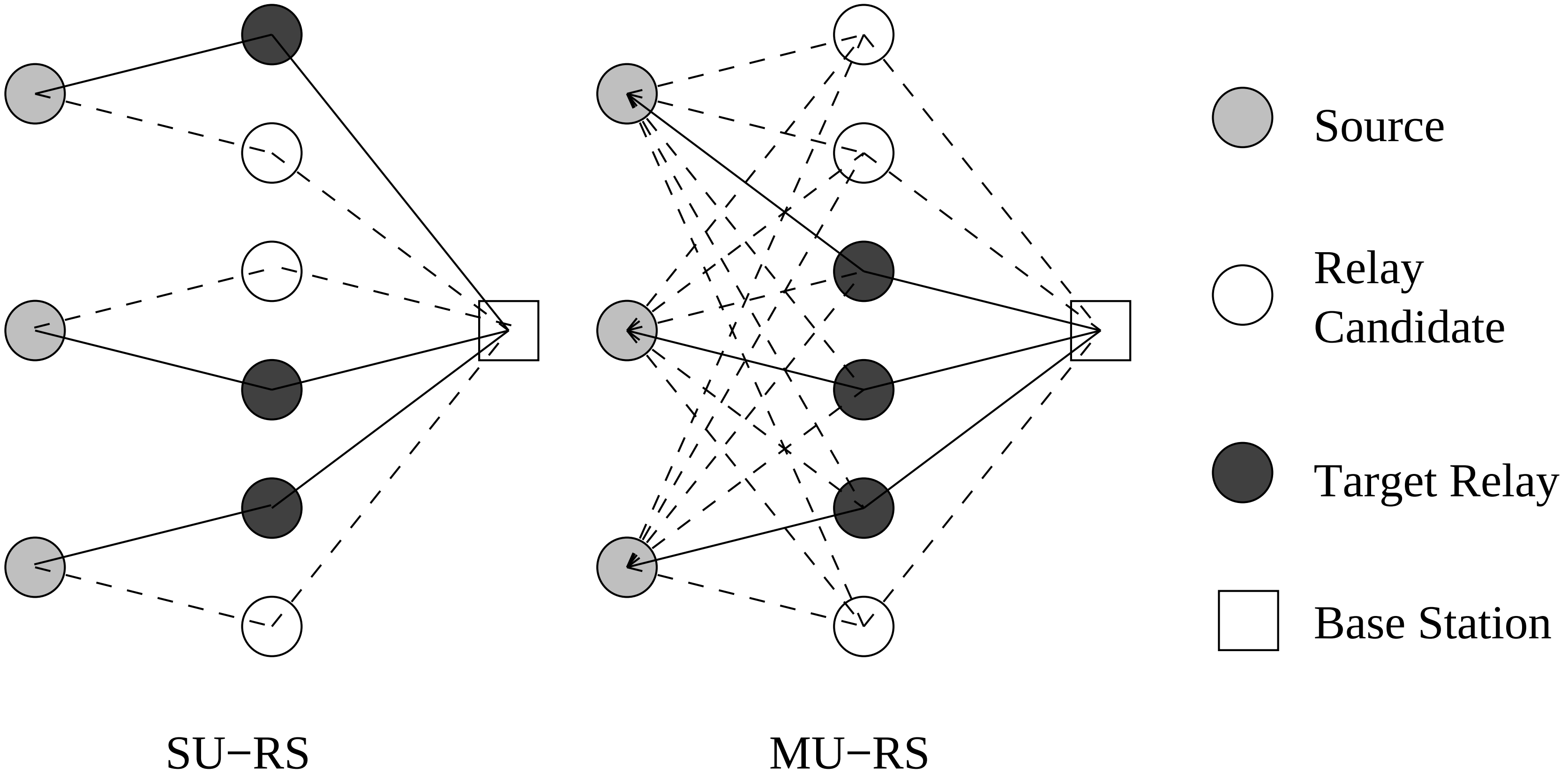
Simulation Results

- Power reduction of JFDEC receiver by ignoring path-loss and shadowing



Opportunistic Cooperative Relaying

- Opportunistic relaying
  - allows a single relay to be selected from a cluster of $J (J > 0)$ inactive MTs, the so-called *Relay Candidates* (RC), depending on which MT provides for the best end-to-end link quality between the source and destination



Relay Selection Schemes

❏ Single-User Relay Selection (SU-RS) for the SDR

- High number of idle MTs, more RCs may be considered
- Each source MT is capable of seeking a target relay from a cluster of J RCs which are independent of the other source MT's RC

$$j_k^{(opt)} = \arg \max_{j \in [0, J-1]} \{\gamma_{j,k}\}$$

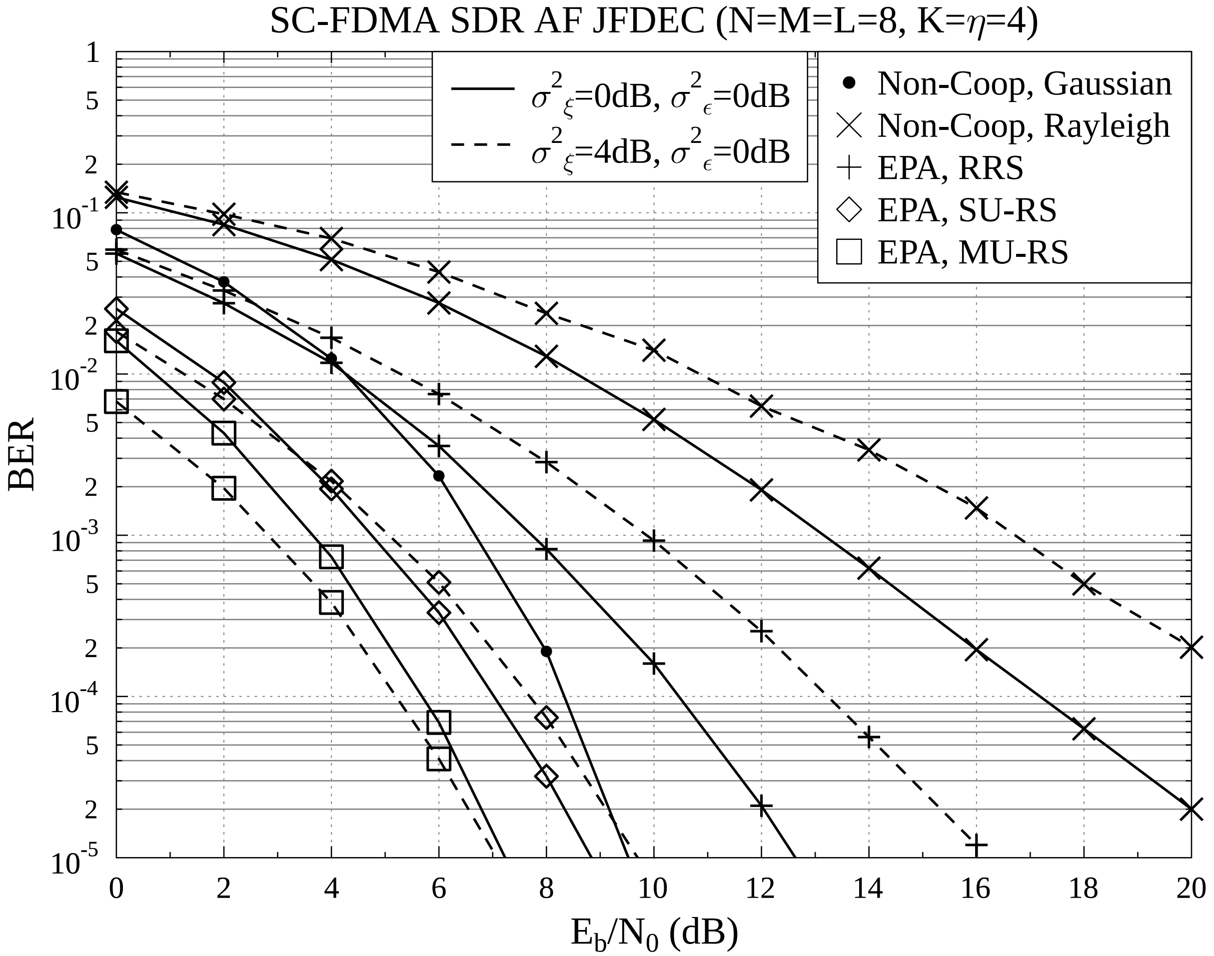
❏ Multi-User Relay Selection (MU-RS) for the SDR

- Low number of inactive MTs results in an insufficient number of available RCs
- A cluster of K source MTs is assocated with a cluster of $J (J \geq K)$ RCs, the system only requires a total of K relays

$$j_{k,i}^{(opt)} = \arg \max_{j \in [0, J-1], k \in [0, K-1]} \{\gamma_{j,k}\}$$

Simulation Results

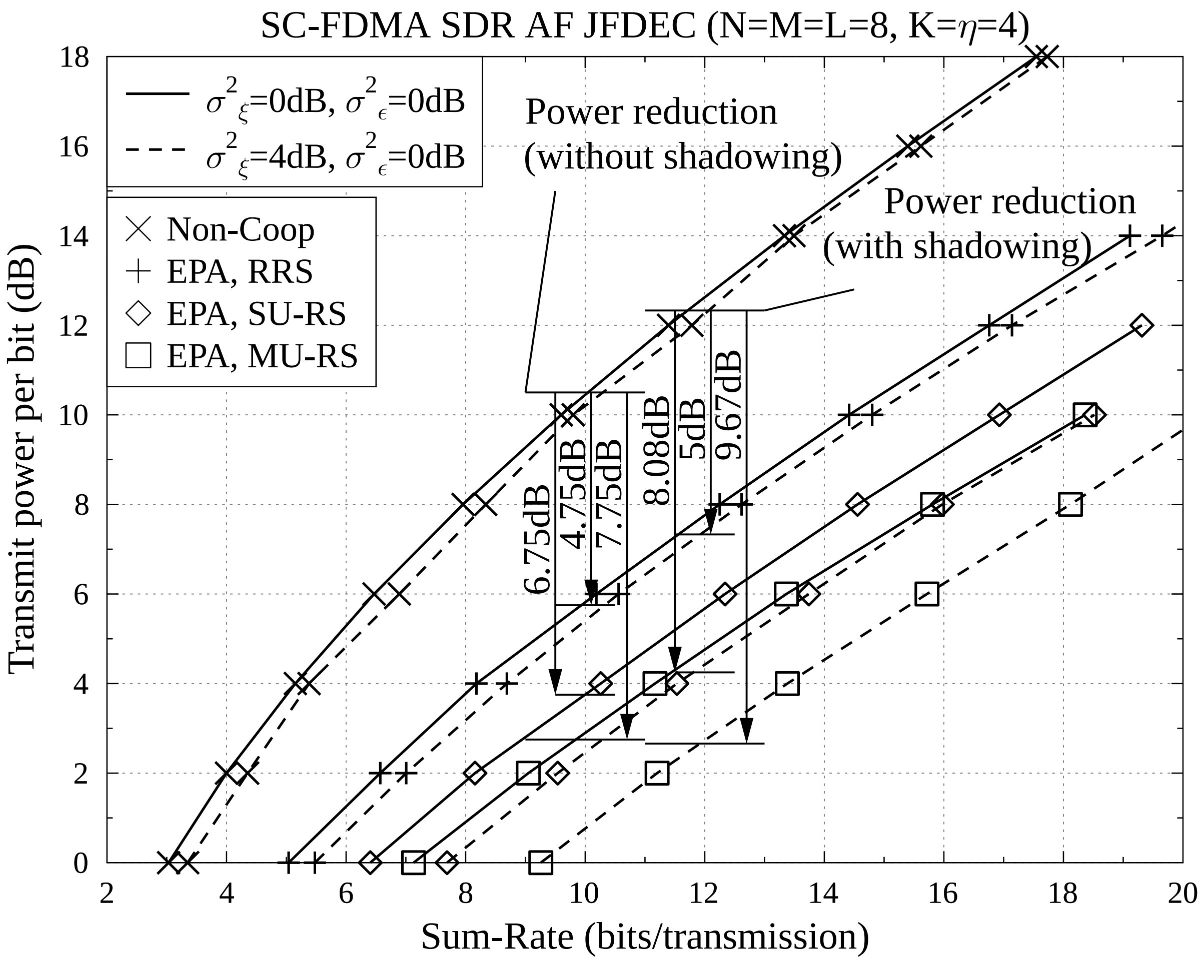
- BER performance of relay selection schemes
  - for path-loss exponent $\eta = 4$, 4 source MTs and total 16 RCs case



Simulation Results

- Power reduction of relay selection schemes

  - for path-loss exponent $\eta = 4$, 4 source MTs and total 16 RCs case



Conclusions

- ❑ Cooperative SC-FDMA was studied
  - Proposed diversity-optimised FDE receiver
    - **achieved 4dB power reduction**
  - Relay selection schemes for opportunistic relaying
    - Over fading channels free freom shadowing:
      SU-RS provides 6.8dB power reduction
      MU-RS provides 7.8dB power reduction
    - Over 4dB shadow fading channels:
      SU-RS provides 8dB power reduction
      MU-RS provides 9.7dB power reduction