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Multi-User Performance of the Amplify-and-Forward Single-Relay Assisted SC-FDMA Uplink

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Outline

- Overview of the state-of-the-art
- Assumptions
- Transmitter model
- Relay model
- Signal processing at the BS's receiver
- Results and discussions
- Conclusions

Key References

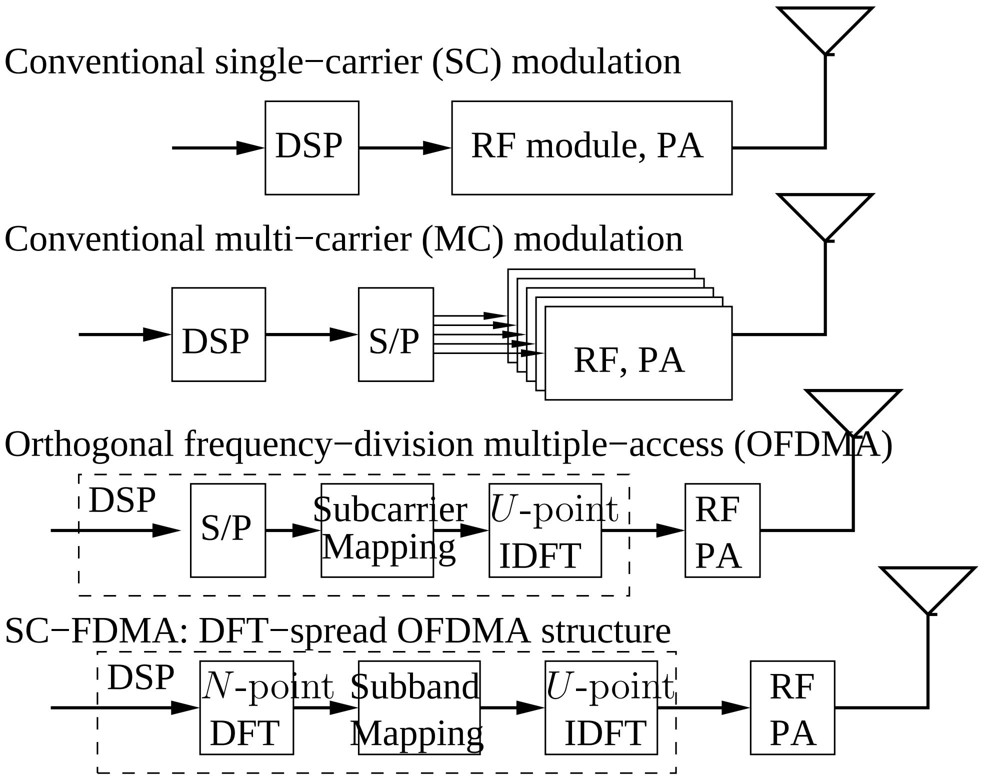
- L.-L. Yang, *Multicarrier Communications*, Wiley, 2009.
- W. Fang, L.-L. Yang and L. Hanzo, “Single-user performance of direct-sequence code-division multiple-access using relay diversity and power allocation”, *IET Communications*, vol. 2, pp. 462–472, Mar. 2008.
- H. G. Myung and J. Lim and D. J. Goodman, “Single carrier FDMA for uplink wireless transmission”, *IEEE Vehicular Technology Magazine*, pp. 30–38, Sept. 2006.
- A. 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/LTE-Advanced prospective
- Green Radio awareness - energy efficiency
- High transmission throughput requirement: broadband rather than narrowband
- Problem: have to mitigate both the large-scale and small-scale fading over dispersive channels

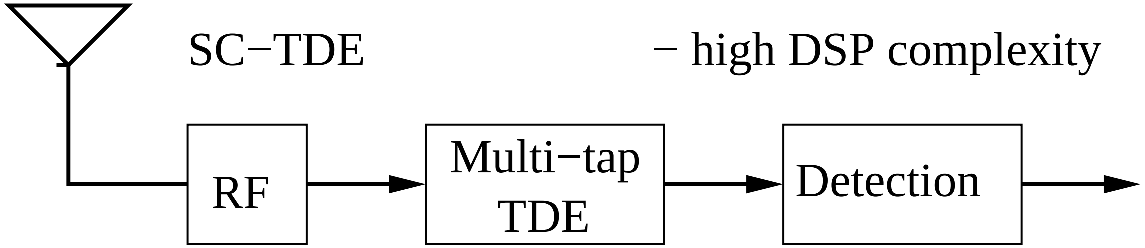
Why SC-FDMA?

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

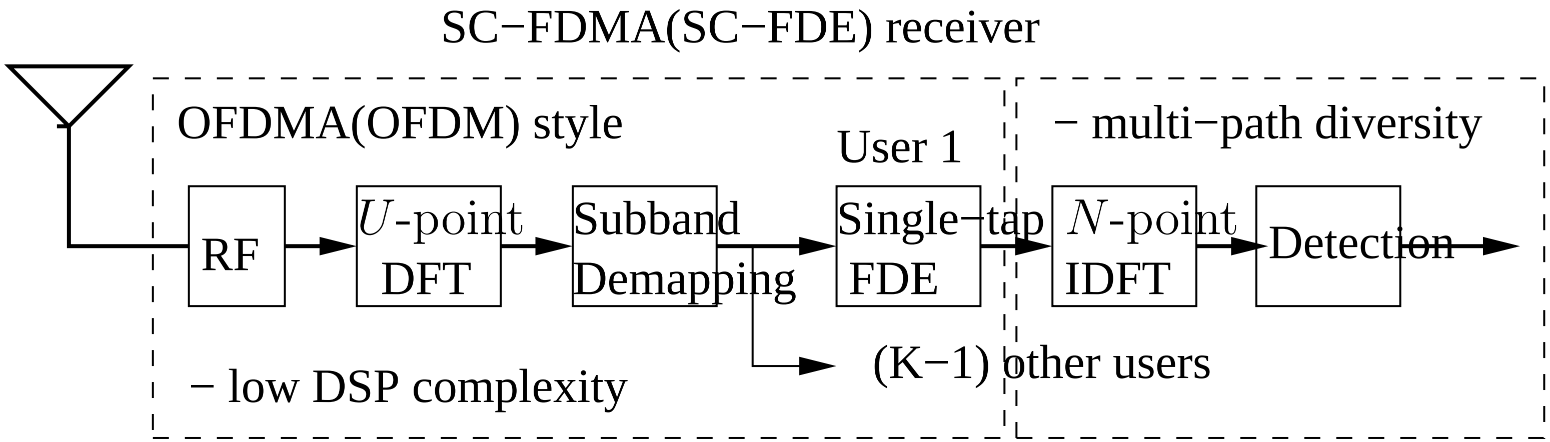


Signal generation	RF module and PA	PAPR	Hardware complexity	Configure flexibility	Multi−path diversity
Time −domain (TD)	Single	Low	Low	Constant −moudulus modulation	Depend on receiver
TD	Multiple	Low	High	Constant −moudulus modulation	No
Frequency −domain (FD)	Single	High	Low	Flexible Reconfig	No
TD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

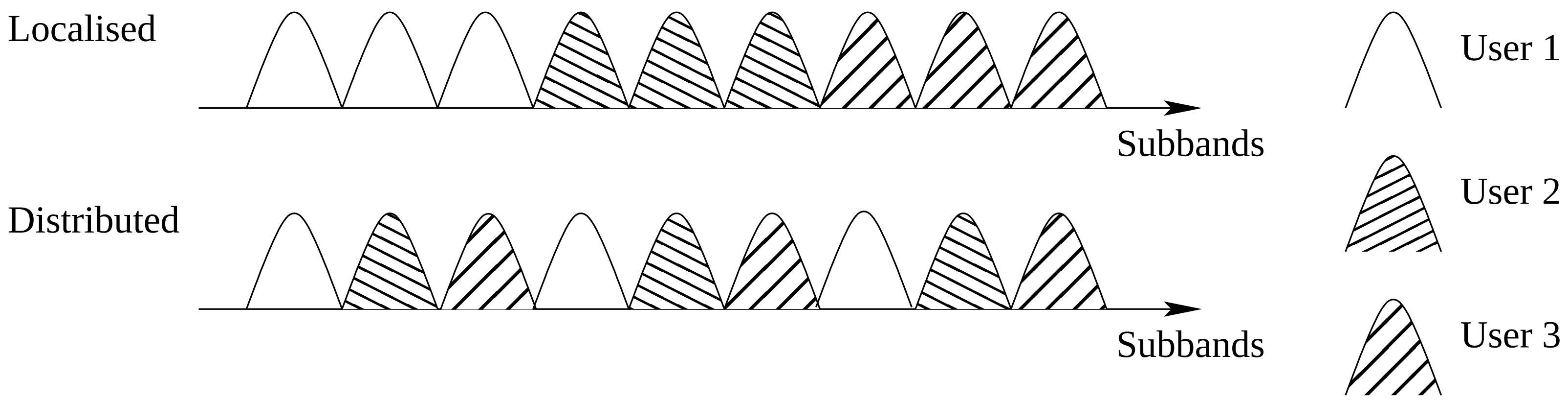
- Digital signal processing (DSP) at receiver
  - Conventional SC receiver: *time-domain equaliser (TDE) with hundreds of filter taps in case of long channel impulse responses imposed by frequency-selective fading*



  - 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



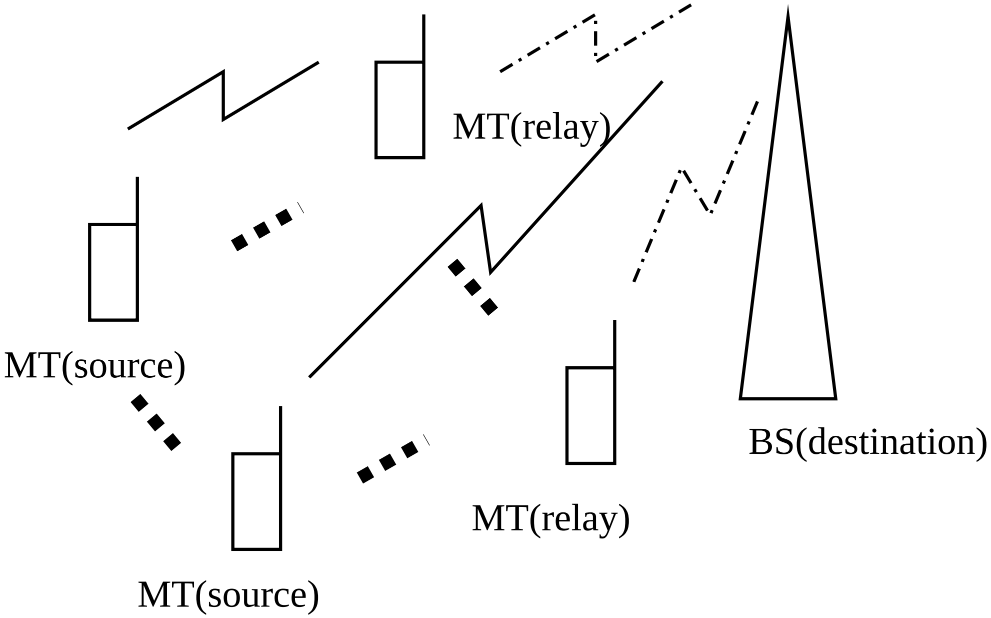
- Distributed mode provides higher *multi-path diversity* gain than localised mode.
- Localised mode may achieve *multi-user diversity* when invoking *channel-dependent scheduling*, it is more suitable for a system in which a few users require high bit-rate.
- Interleaved mode is a special case of the 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)
- Approaches
  - Conventional colocated MIMO elements
  - Distributed MIMO with relay
  - Distributed forward error correction (FEC) coding
  - Multi-user MIMO, multi-cell cooperation: transmitter preprocessing
  - Resource management: dynamic spectrum allocation, multi-user scheduling and relay selection, etc

Frequency-Domain Amplify-and-Forward Single-Relay Assisted SC-FDMA Uplink

- Our proposed systems are capable of providing:
  - Cooperative diversity gain
  - Multipath diversity gain
- Additionally,
  - Free of multiuser interference (MUI)
  - Reduced AF noise
  - Low PAPR
  - Low DSP complexity at the receiver



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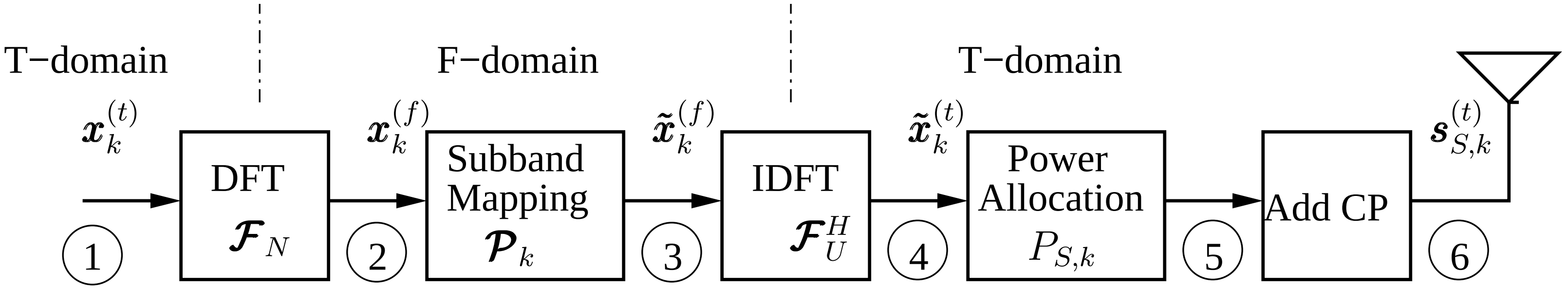
Assumptions

- BPSK modulation without FEC.
- Pathloss and shadowing are ignored, which implies assuming perfect power control.
- Complex-valued additive white Gaussian noise (AWGN) $\mathcal{CN}(0, \sigma_N^2)$ at the relay and BS
- Perfect channel state information at the receiver (CSIR) of the BS.
- Orthogonal subbands of the DFT-S-OFDM signals, avoiding MUI among the source MT.
- A sufficiently long cyclic-prefix (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.
- The relays are assigned without selection.

Source MT Transmitter

❑ DFT-spread-OFDMA style transmitter



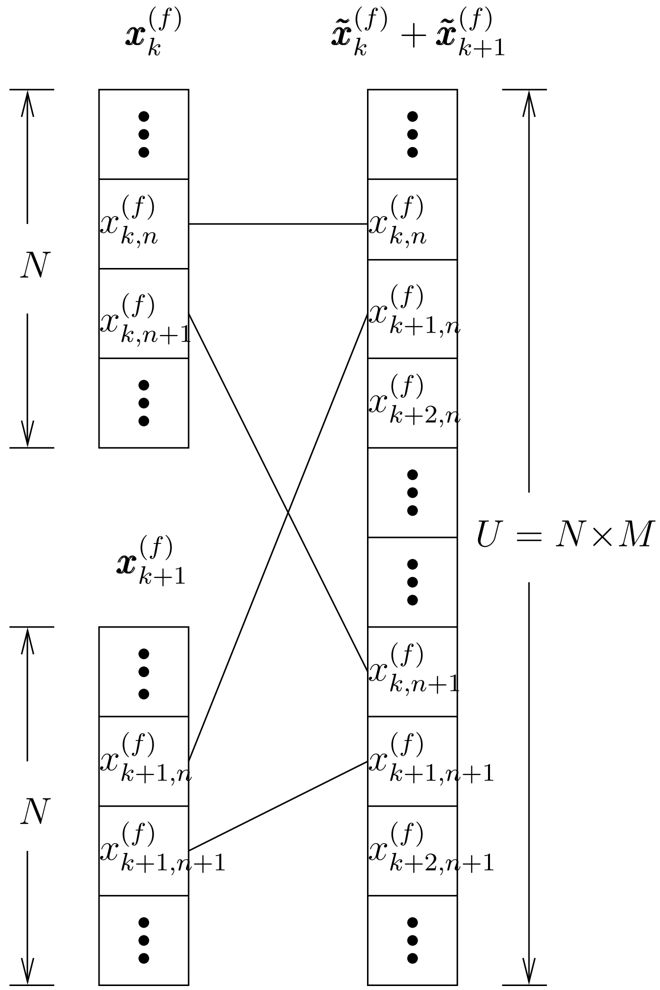
- k-th user's N consecutive TD symbol in the vector $\boldsymbol{x}_k^{(t)}$
- Bandwidth (BW) expansion factor M supports a maximum of M users
- N-point FFT matrix $\boldsymbol{\mathcal{F}}_N$ offers a normalised BW of N per user
- U-point IFFT matrix $\boldsymbol{\mathcal{F}}_U^H$ provides the total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

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

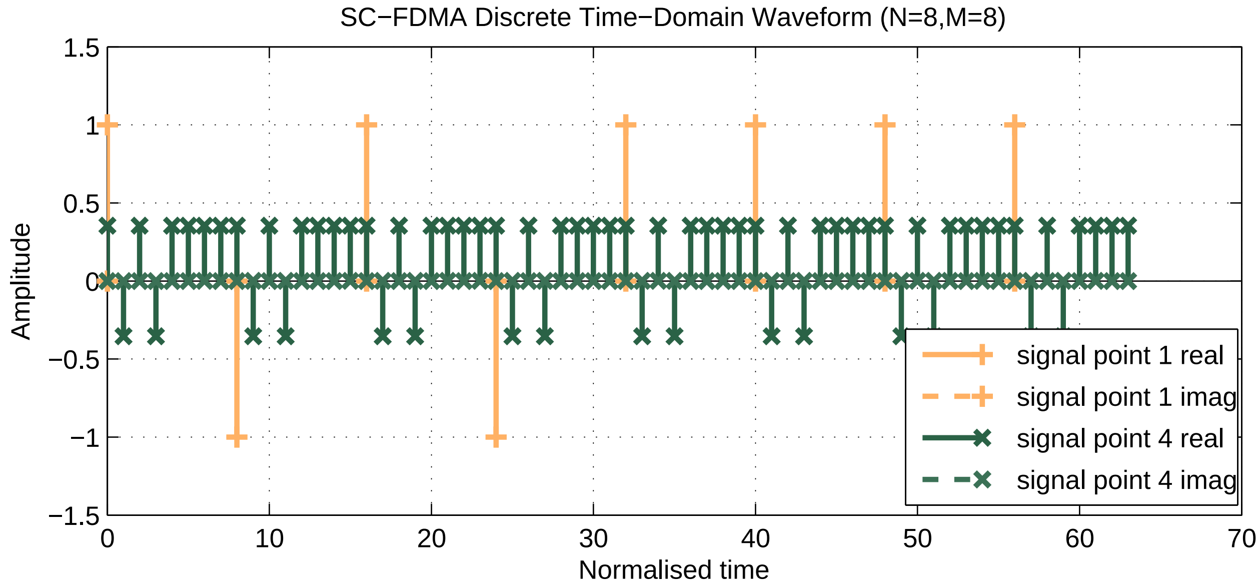
$$\mathcal{P}_{k,un} = \begin{cases} 1, & \text{for } u = nM + k \\ 0, & \text{otherwise} \end{cases}$$

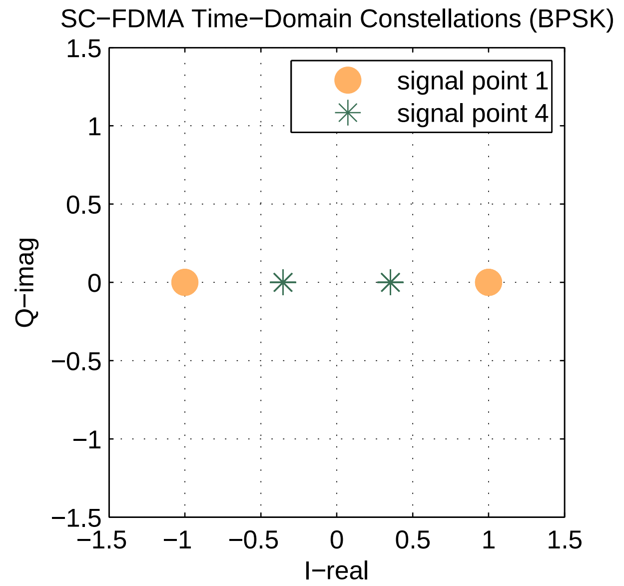
- Transmitted signal before inserting CP

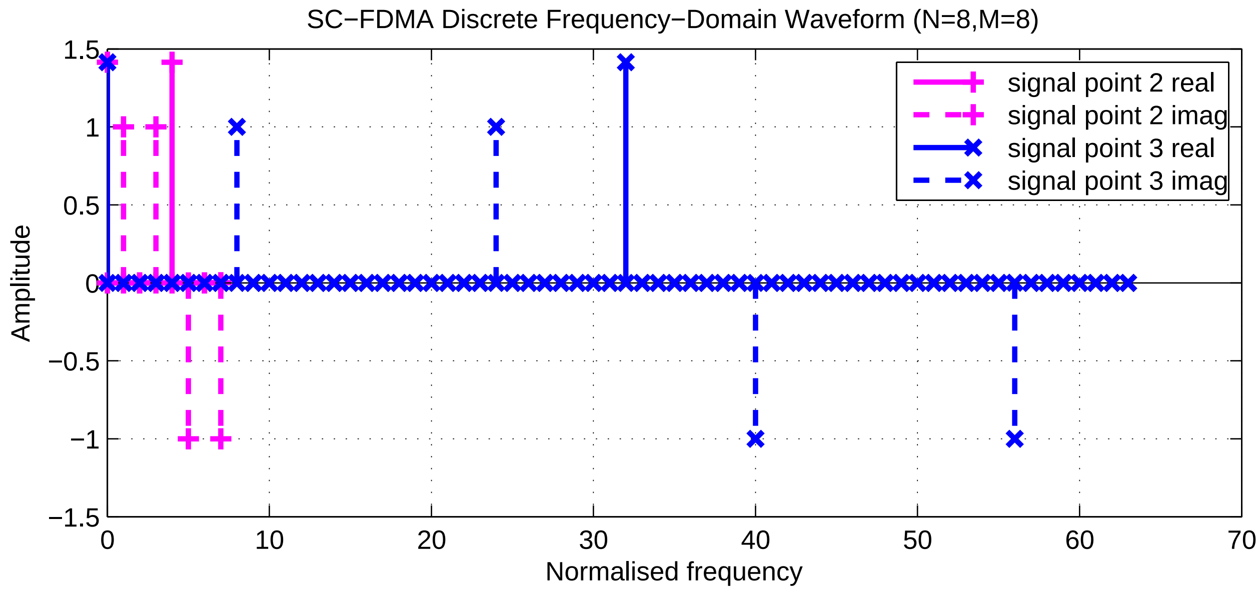
$$\boldsymbol{s}_{S,k}^{(t)} = \sqrt{P_{S,k}} \boldsymbol{\mathcal{F}}_U^H \boldsymbol{\mathcal{P}}_k \boldsymbol{\mathcal{F}}_N \boldsymbol{x}_k^{(t)}$$

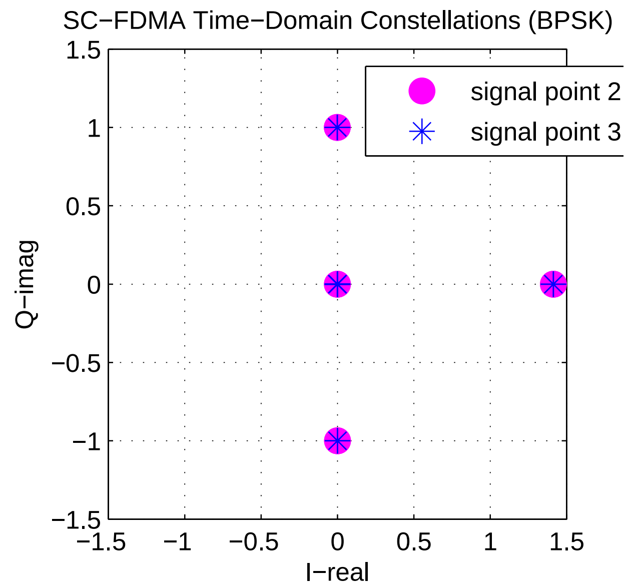


Interleaved subband mapping


SC−FDMA Discrete Time−Domain Waveform (N=8,M=8)
Amplitude
Normalised time
signal point 1 real
signal point 1 imag
signal point 4 real
signal point 4 imag

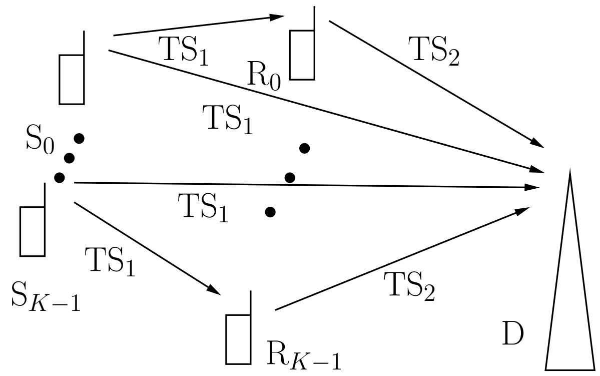

SC−FDMA Time−Domain Constellations (BPSK)
Q−imag
I−real
signal point 1
signal point 4


SC−FDMA Discrete Frequency−Domain Waveform (N=8,M=8)
Amplitude
Normalised frequency
signal point 2 real
signal point 2 imag
signal point 3 real
signal point 3 imag

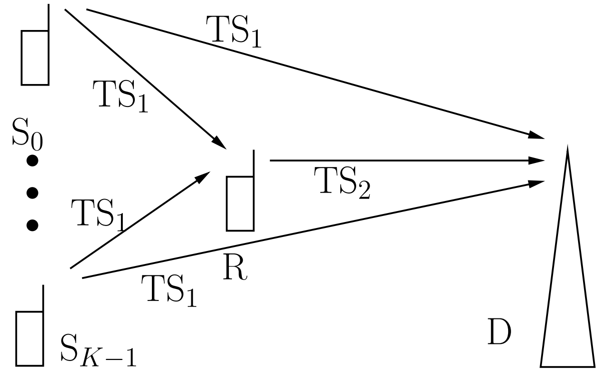

SC−FDMA Time−Domain Constellations (BPSK)
Q−imag
I−real
signal point 2
signal point 3

Relaying Topologies

- Direct Transmission
  - Time-slot 1: $\boldsymbol{r}_{SD}^{(t)} = \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{SD,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}$
- Single-Dedicated-Relaying (SDR):
  - K sources and K relays
  - Transmitted power constraint: $P_{S,k} + P_{R,k} = 1$
  - Time-slot 1: $\boldsymbol{r}_{SR,k}^{(t)} = \tilde{\boldsymbol{H}}_{SR,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{R,k}^{(t)}$
  - Time-slot 2: $\boldsymbol{r}_{RD}^{(t)} = \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{RD,k}^{(t)} \boldsymbol{s}_{R,k}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}$
- Single-Shared-Relaying (SSR):
  - a cluster of K sources, single relay
  - Transmitted power constraint: $P_{S,k} + P_{R,k} = 1$, $P_R = \sum_{k=0}^{K-1} P_{R,k} = 1$
  - Time-slot 1: $\boldsymbol{r}_{SR}^{(t)} = \sum_{k=0}^{K-1} \tilde{\boldsymbol{H}}_{SR,k}^{(t)} \boldsymbol{s}_{S,k}^{(t)} + \tilde{\boldsymbol{n}}_{R}^{(t)}$
  - Time-slot 2: $\boldsymbol{r}_{RD}^{(t)} = \tilde{\boldsymbol{H}}_{RD}^{(t)} \boldsymbol{s}_{R}^{(t)} + \tilde{\boldsymbol{n}}_{D1}^{(t)}$



SDR



SSR

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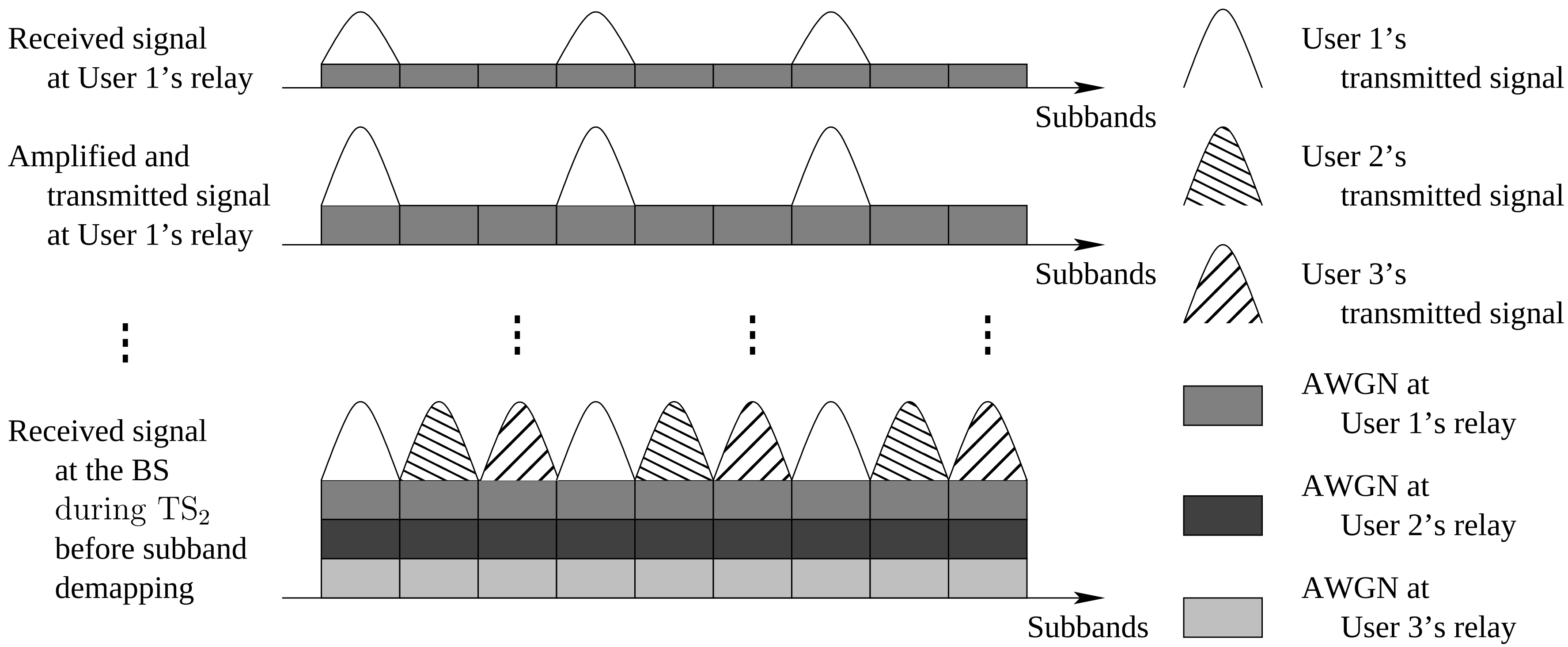
Cooperative Strategies

- Conventional TD-AF
  - Analogue AF by the same factor β in all subbands, but different β for SDR and SSR.
  - SDR: For the k-th user's received signal, the noise encountered at the BS in the FD includes the equivalent relaying noise imposed by the K AF relays and the noise directly contributed by the BS's receiver during the 2-nd time-slot.



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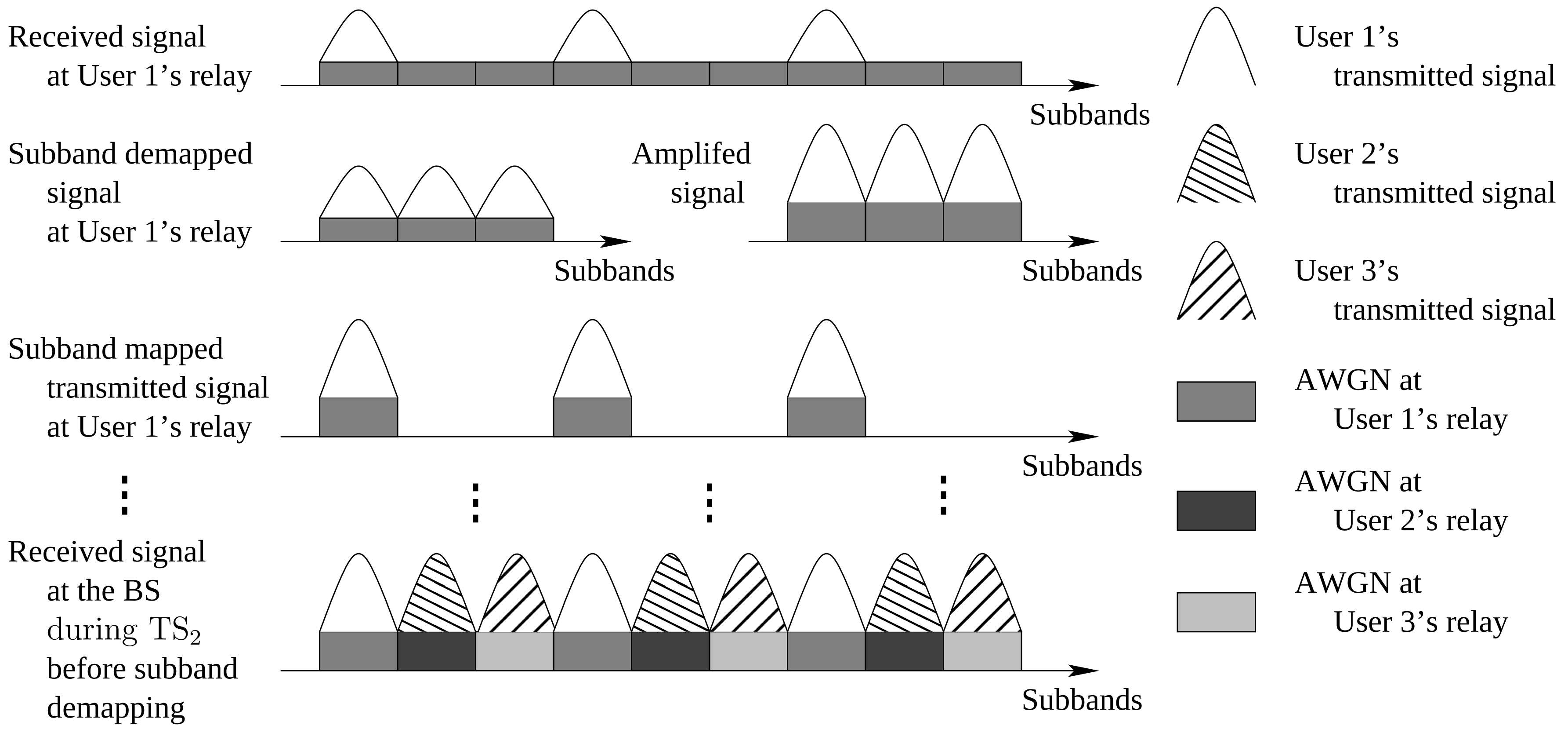
- FD-AF combined with subband remapping



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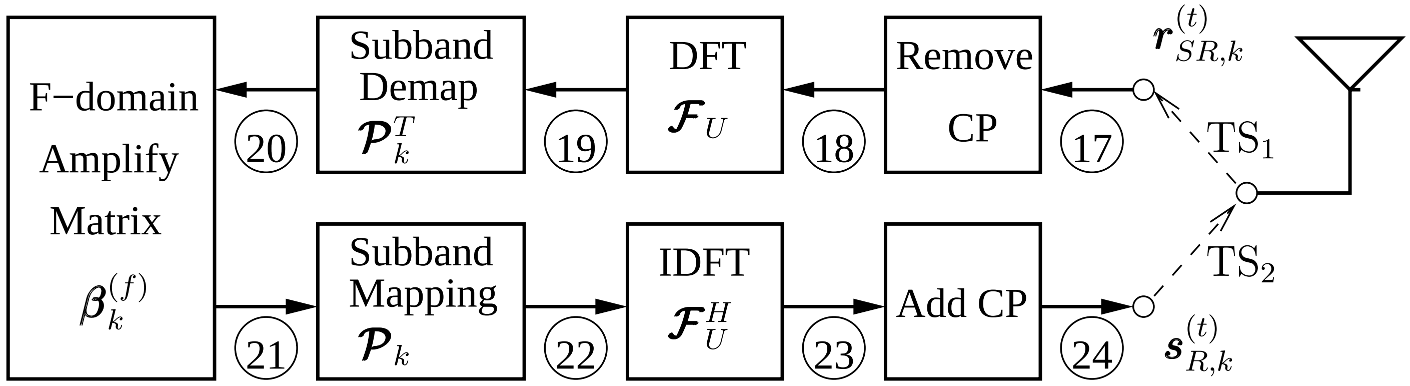


- Removing noise in other user's bands
- Avoiding MUI from other source MTs and relays
- FD operated amplification by a subband-specific factor β_n in the n-th subband
- The k-th user's signal forwarded by the relay is at the same frequency as that in the source MT
- Same β_n for both SDR and SSR: $\beta_{kn}^{(f)} = \sqrt{P_{R,k}/[P_{S,k}|h_{SR,kn}^{(f)}|^2 + \sigma_N^2]}$
- Allow the BS to process the two-hop relay link in the FD by a simple single-tap FDE.

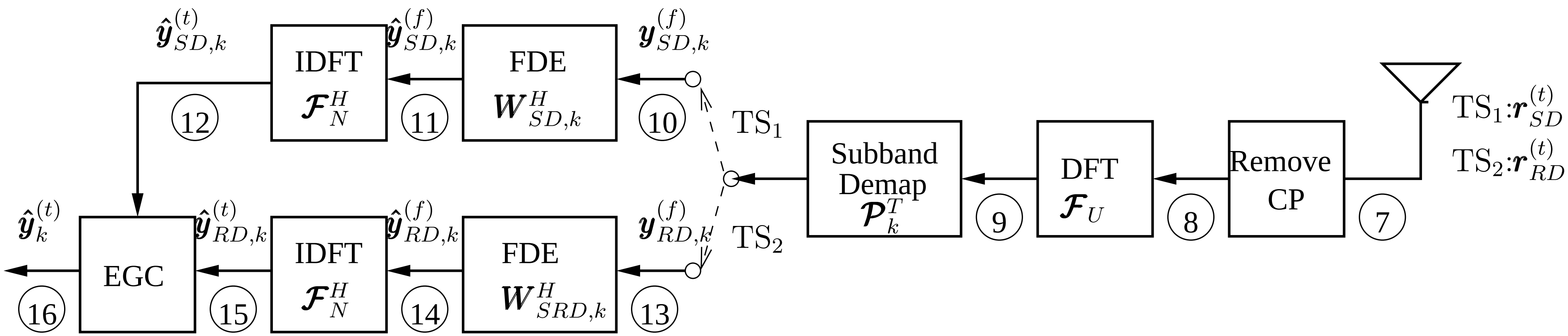
Signal Processing at the BS's Receiver

- Subband demapping $\mathcal{P}_k^T$ guarantees that the k-th user's signal is free from MUI
- The k'-th user's received signals after CP removal and subband demapping:
  - Direct link:

$$\boldsymbol{y}_{SD,k'}^{(f)} = \sqrt{P_{S,k'}}\boldsymbol{H}_{SD,k'}^{(f)}\boldsymbol{x}_{k'}^{(f)} + \boldsymbol{n}_{D0}^{(f)}$$

  - Relay link:

$$\boldsymbol{y}_{RD,k'}^{(f)} = \sqrt{P_{S,k'}}\boldsymbol{H}_{RD,k'}^{(f)}\boldsymbol{\beta}_{k'}^{(f)}\boldsymbol{H}_{SR,k'}^{(f)}\boldsymbol{x}_{k'}^{(f)} + \bar{\boldsymbol{n}}_{D1}^{(f)}$$



- MMSE-FDE followed by TD-EGC
- FDE weights at the n-th subband for the k'-th user:
  - Direct link:

$$w_{SD,k'n} = P_{S,k'} h^{(f)}_{SD,k'n} / (P_{S,k'} |h^{(f)}_{SD,k'n}|^2 + \sigma_N^2)$$

  - Relay link:

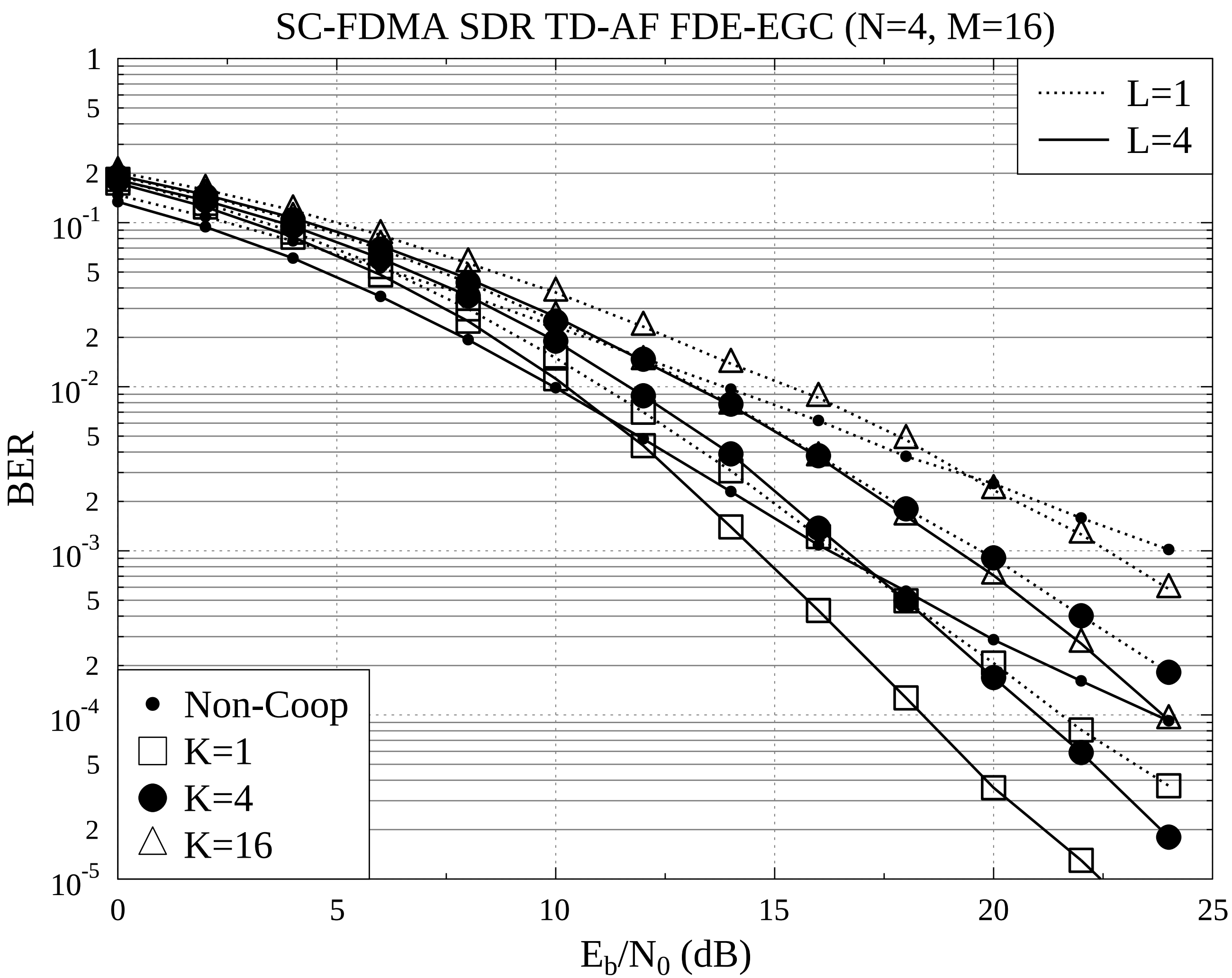
$$w_{SRD,k'n} = \frac{P_{S,k'} \beta^{(f)}_{k'n} h^{(f)}_{RD,k'n} h^{(f)}_{SR,k'n}}{P_{S,k'} (\beta^{(f)}_{k'n})^2 |h^{(f)}_{RD,k'n}|^2 |h^{(f)}_{SR,k'n}|^2 + \mathcal{N}_{D1,n}}$$

- Time-domain equal-gain combined signal:

$$\hat{\boldsymbol{y}}^{(t)}_{k'} = \boldsymbol{\mathcal{F}}^H_N \hat{\boldsymbol{y}}^{(f)}_{SD,k'} + \boldsymbol{\mathcal{F}}^H_N \hat{\boldsymbol{y}}^{(f)}_{RD,k'}$$

Results and discussions

- Conventional TD-AF scheme upon varying the number of users for SDR
  - Multi-path fading: cooperative diversity gain is only achieved at high SNRs for a single-user scenario.
  - The cooperative diversity gains of SDR are eroded in a multi-user scenario, when K is increased.
  - Multipath diversity gain is retained, regardless of the number of users.



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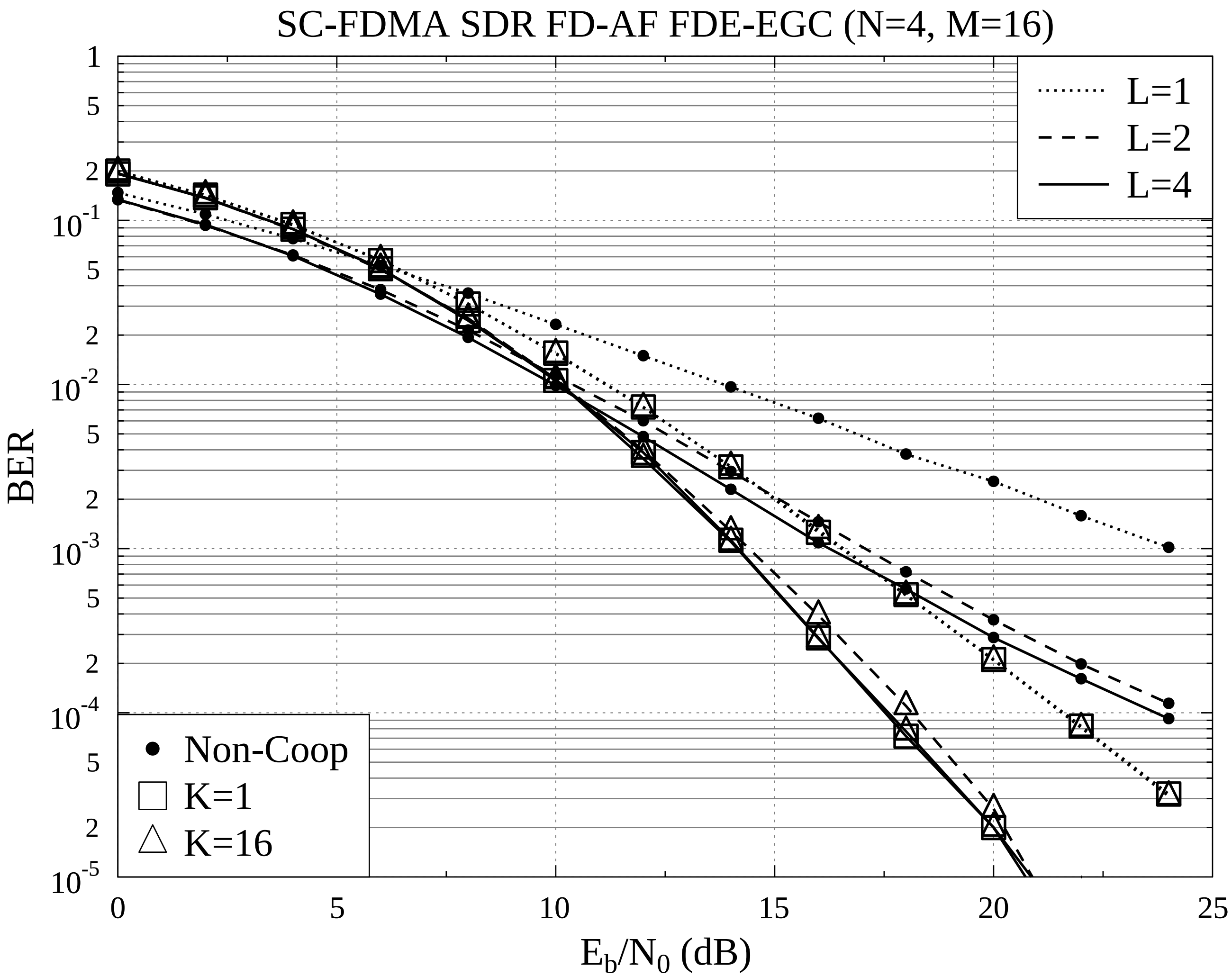
- Proposed FD-AF scheme upon varying the number of multipath components for SDR
  - Same performance for single-user and multi-user scenarios
  - Same performance for single-path and multi-path fading channels
  - Improved performance of FD-AF compared to TD-AF



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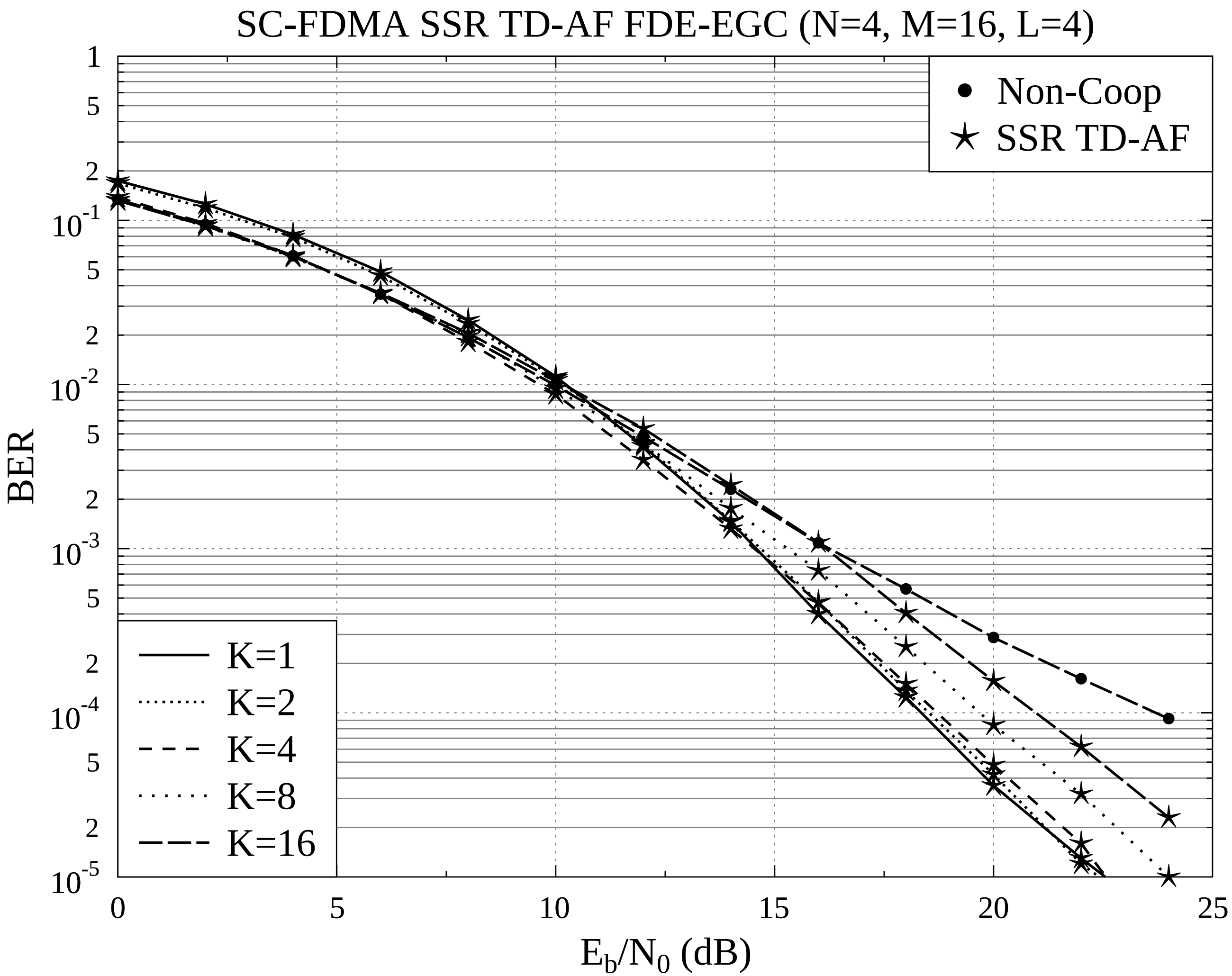
- ❑ Conventional TD-AF scheme upon varying the number of users for SSR
  - Cooperative diversity gain can be achieved in terms of the number of users
  - Cooperative diversity aided performance is eroded by the interference inflicted by the dispersive channel.



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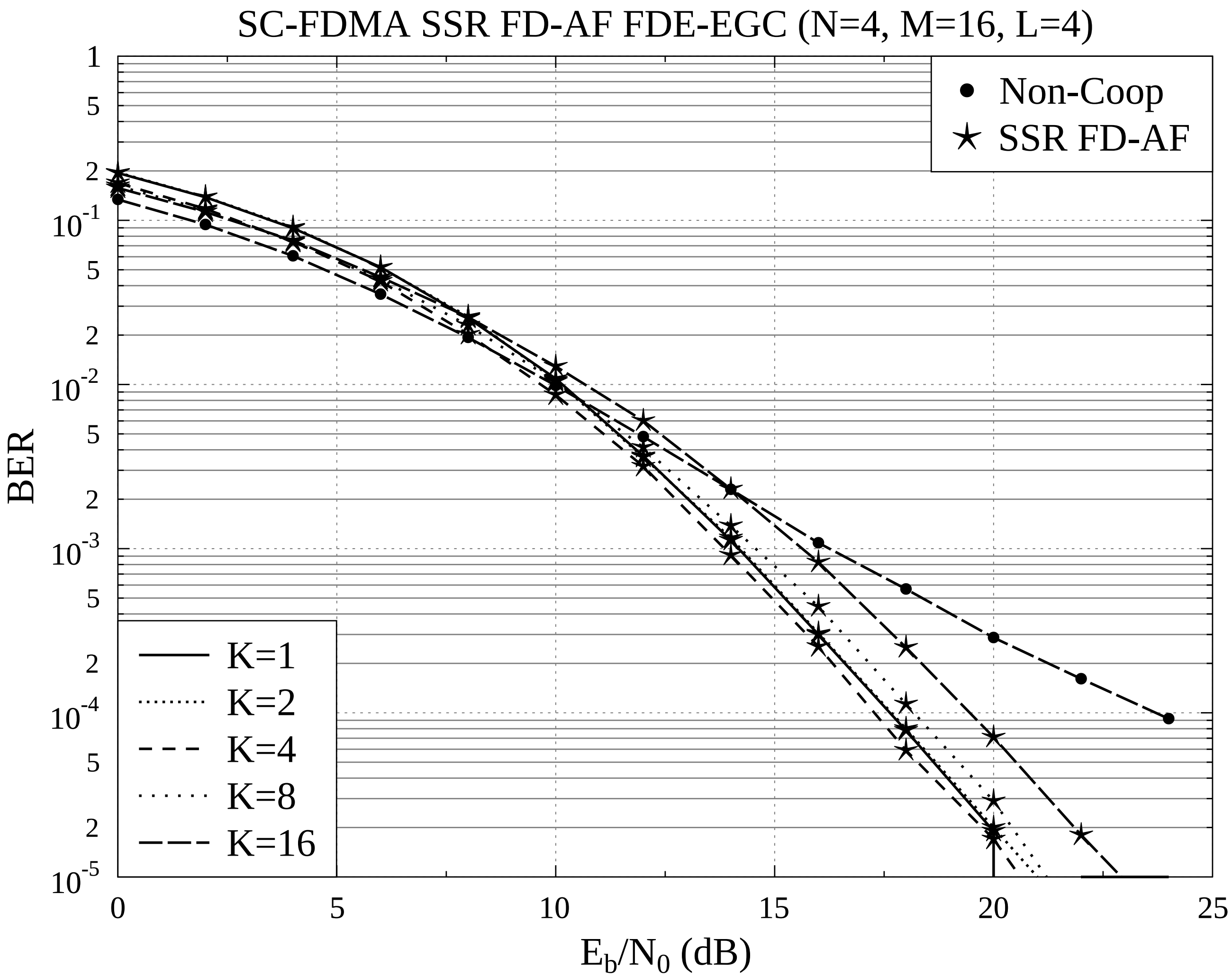
- Proposed FD-AF scheme upon varying the number of users for SSR
    - Interference imposed by the dispersive channel are suppressed by including an subband-based AF at relay and the MMSE-FDE at the BS.



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Conclusions

- ❏ Cooperative SC-FDMA was studied
  - Two relaying topologies - *satisfying different transmission conditions*
  - Orthogonal cooperation and EGC - *attaining cooperative diversity gain*
  - DFT-S-OFDMA and FDE - *achieves multi-path diversity*
  - Subband-based FD-AF single-relay - *eliminates the MUI among the source MT and relays*