On Distributed Space-Time Coding Techniques for Cooperative Wireless Networks and their Sensitivity to Frequency Offsets

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Distributed Space-Time Coding Techniques

- **Space-time coding (STC)** techniques for **multiple-antenna** wireless communication systems
  - **Performance** of wireless systems often limited by **fading** due to **multipath** signal propagation.
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  - Multiple (single-antenna) nodes cooperate in order to perform a **joint transmission strategy**.

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  - Multiple (single-antenna) nodes cooperate in order to perform a **joint transmission strategy**.

$\Longrightarrow$ Nodes share their antennas by using a **distributed** STC scheme.

Examples for Cooperative Wireless Networks

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  Signal transmitted by a given **source node** is received by several **relay nodes** and forwarded to a **destination node**.

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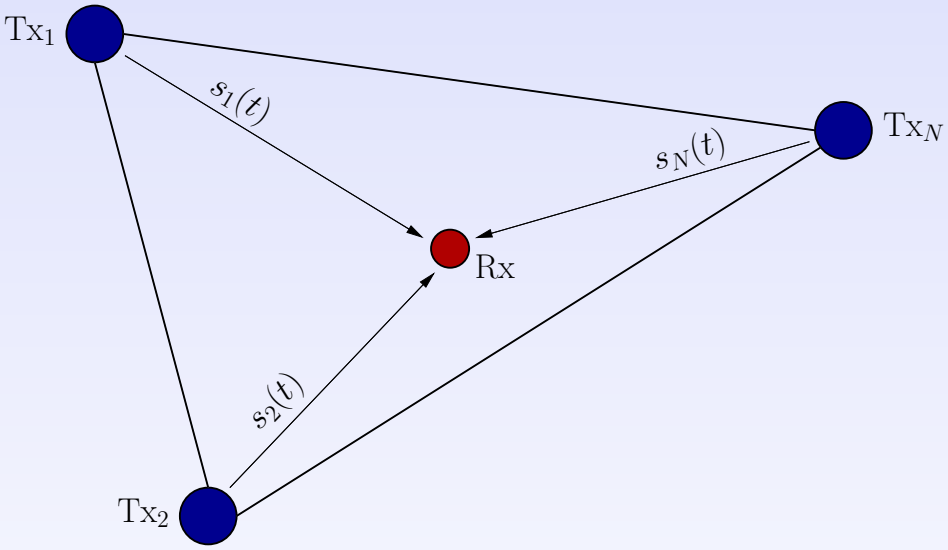
$\Longrightarrow$ **Distributed STC techniques suitable for both simulcast and relay-assisted networks.**

Simulcast Network

- N **transmitting** nodes $(\mathrm{Tx}_1,\ldots,\mathrm{Tx}_N)$, one **receiving** node (Rx)



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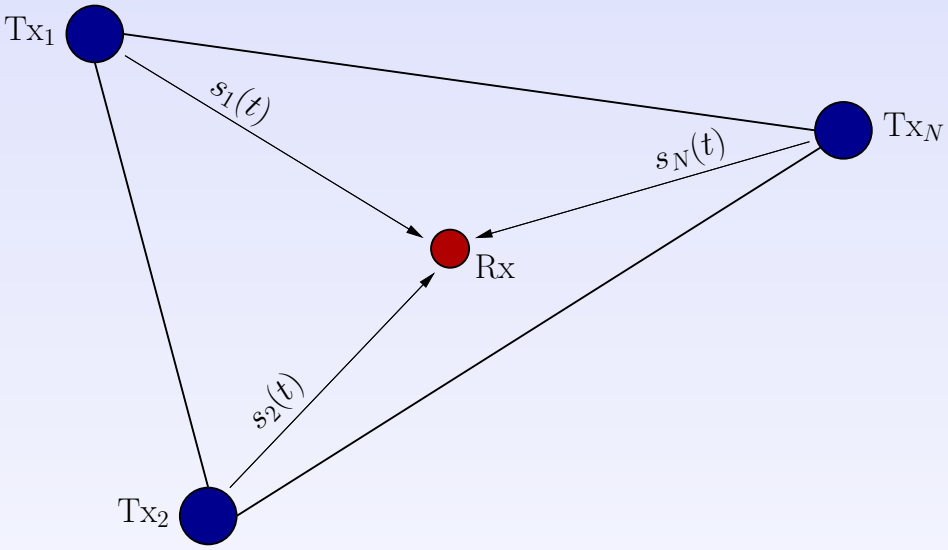

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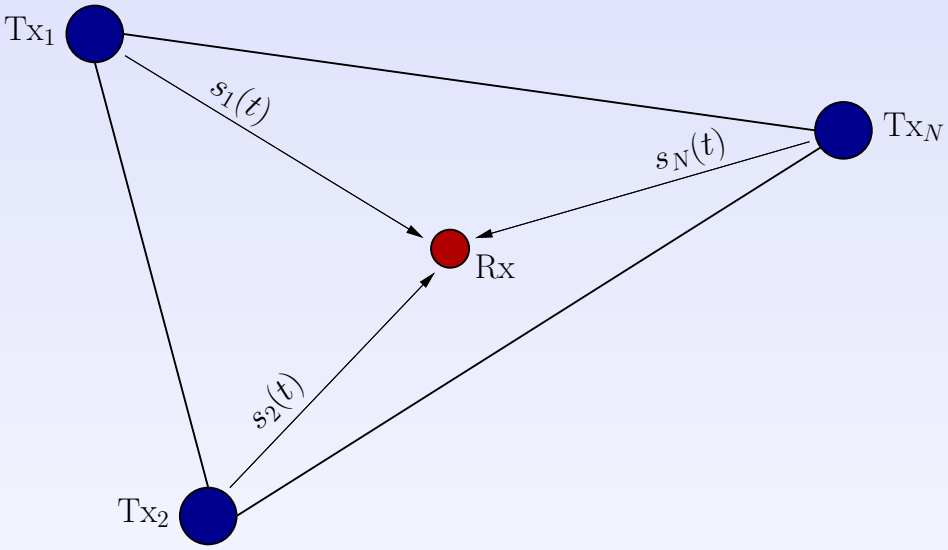

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Example:

Space-time block codes (STBCs) from orthogonal designs (Tarokh et al. '99)

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- Focus on the Alamouti scheme (orthogonal STBC for $N=2$ transmitters).

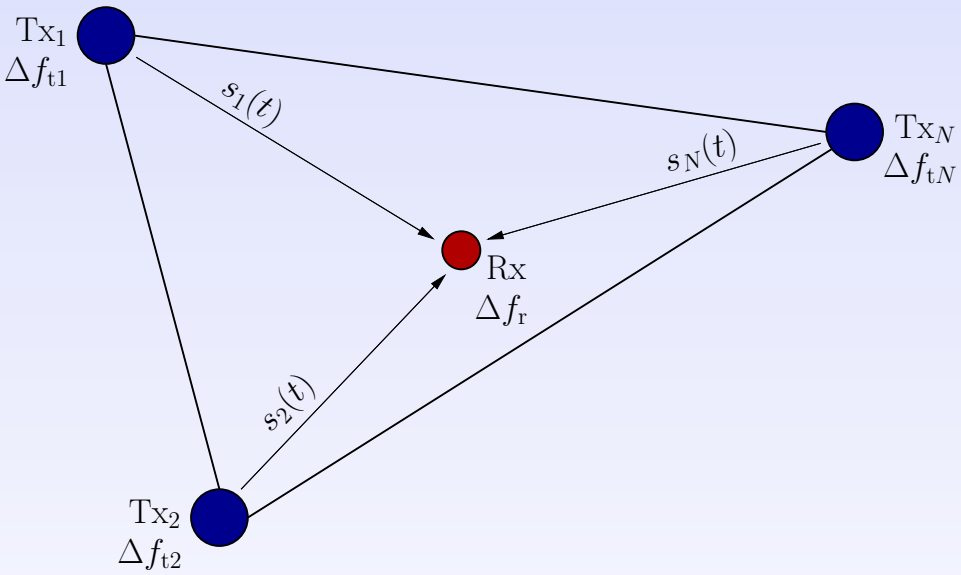
Outline

- **Influence of the Frequency Offsets**
  - Conventional Alamouti Detection
  - Zero-Forcing Detection and Maximum-Likelihood Detection
  - Bit Error Probability
- **Simulation Results**
- **Frequency-Offset Estimation**
- **Conclusions**

Influence of the Frequency Offsets

- **Overall frequency offset** for transmitted signal $s_\nu(t)$:

$$\Delta f_\nu = \Delta f_{\mathrm{t}\nu} - \Delta f_{\mathrm{r}}.$$



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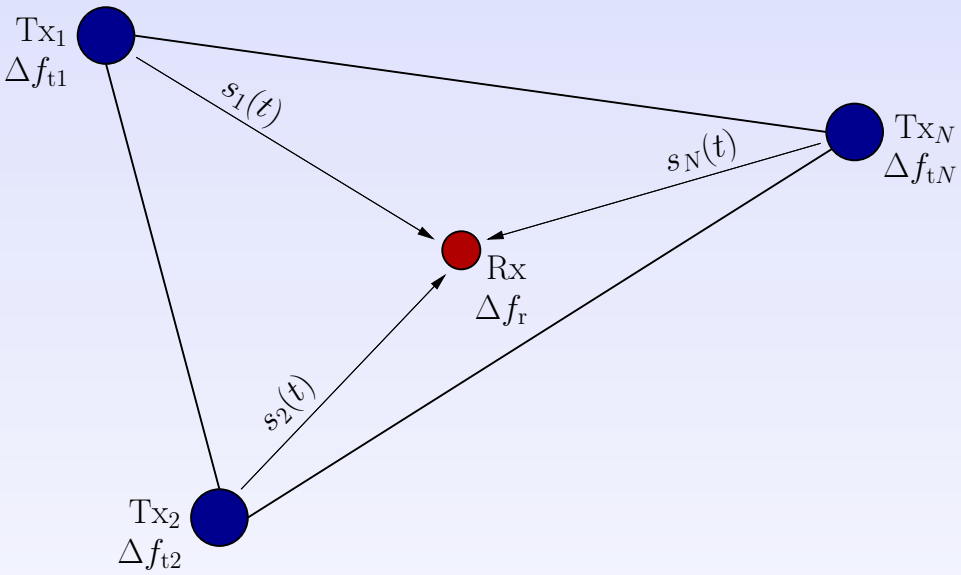

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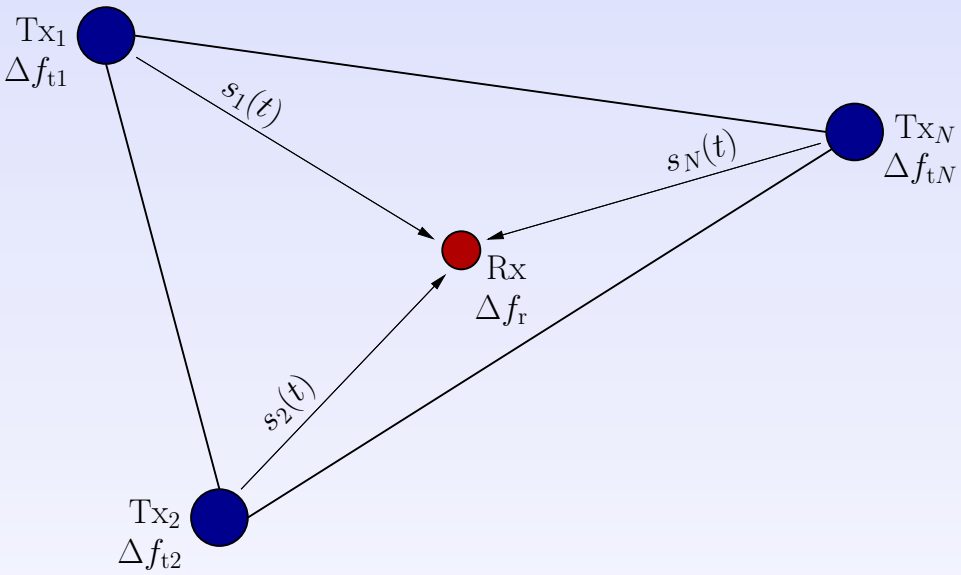

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- Quasi-static frequency-flat fading:

  Complex **channel coefficients** $h_1, \ldots, h_N$.

$\Longrightarrow$ Frequency offsets cause **time-varying phase**:

$$\overline{h}_\nu[k] \;\doteq\; h_\nu \cdot \mathrm{e}^{\mathrm{j}2\pi\zeta_\nu k}$$

Ideal Local Oscillators – Alamouti-Detection

- **Distributed Alamouti scheme** ($N = 2$ Tx nodes); **ideal** local oscillators (LOs), $\zeta_1 = \zeta_2 = 0$

$$\Longrightarrow \quad \mathbf{y}[k] \;=\; \mathbf{H}_{\mathrm{eq}}\,\mathbf{x}[k] + \mathbf{n}[k] \qquad (1)$$

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$\mathbf{y}[k]$: Received samples, $\mathbf{x}[k]$: Transmitted symbols, $\mathbf{n}[k]$: Noise samples,

$\mathbf{H}_{\mathrm{eq}} = \begin{bmatrix} h_1 & -h_2 \\ h_2^* & h_1^* \end{bmatrix}$: Equivalent **orthogonal** (2x2)-channel matrix.

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$\Longrightarrow$ **Alamouti detection:**

$$\begin{aligned} \mathbf{z}[k] \;\doteq\; \mathbf{H}_{\mathrm{eq}}^{\mathrm{H}}\,\mathbf{y}[k] \;&=\; \mathbf{H}_{\mathrm{eq}}^{\mathrm{H}}\mathbf{H}_{\mathrm{eq}}\,\mathbf{x}[k] \;+\; \mathbf{H}_{\mathrm{eq}}^{\mathrm{H}}\,\mathbf{n}[k] \\ &=\; \left(|h_1|^2 + |h_2|^2\right)\,\mathbf{x}[k] \;+\; \mathbf{H}_{\mathrm{eq}}^{\mathrm{H}}\,\mathbf{n}[k] \qquad (2) \end{aligned}$$

Non-Ideal Local Oscillators – Alamouti-Detection

- **Channel matrix** $\mathbf{H}_{\mathrm{eq}}$ becomes

$$\overline{\mathbf{H}}_{\mathrm{eq}}[k] = \begin{bmatrix} \overline{h}_1[k] & -\overline{h}_2[k] \\ \overline{h}_2^*[k+1] & \overline{h}_1^*[k+1] \end{bmatrix}. \quad (3)$$

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(ii) **Non-perfect estimates** $\hat{\zeta}_\nu \doteq \zeta_\nu + \epsilon_\nu$ of the frequency offsets available at the receiver

$\Longrightarrow$ Receiver uses $\overline{\mathbf{H}}_{\mathrm{eq},\epsilon}^{\mathrm{H}}[k] = \begin{bmatrix} h_1^* \cdot \mathrm{e}^{-\mathrm{j}2\pi\hat{\zeta}_1 k} & h_2 \cdot \mathrm{e}^{\mathrm{j}2\pi\hat{\zeta}_2(k+1)} \\ -h_2^* \cdot \mathrm{e}^{-\mathrm{j}2\pi\hat{\zeta}_2 k} & h_1 \cdot \mathrm{e}^{\mathrm{j}2\pi\hat{\zeta}_1(k+1)} \end{bmatrix}$ for detection.

Depending on the quality of the estimates $\hat{\zeta}_\nu$, more or less severe **orthogonality loss**.

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(iii) Frequency offsets **completely unknown** at the receiver $\Longrightarrow$ Receiver uses $\mathbf{H}_{\mathrm{eq}}^{\mathrm{H}}$ for detection.

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(a) **Zero-forcing** (ZF) detection: Use inverse matrix for detection instead of hermitian conjugate.

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- **Performance** of ZF detection is virtually the same as that of ML detection in all cases.
- Given ideal LOs Alamouti detection, ZF detection, and ML detection are **equivalent**.

Bit Error Probability

- Non-ideal LOs, Alamouti detection or ZF detection
- Quasi-static frequency-flat fading
- QPSK symbols $x[k]$ with **Gray mapping** $[b_{1k}b_{2k}] \mapsto x[k]$:

$$[00] \mapsto \exp[\mathrm{j}\,\pi/4] \qquad [01] \mapsto \exp[\mathrm{j}\,3\pi/4]$$
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- $z[k]$ corresponding symbol after Alamouti detection/ ZF detection
- Let $d_{\mathrm{Re}}[k]$, $d_{\mathrm{Im}}[k]$ denote real and imaginary part of $z[k]$ for high SNRs ($E_s/N_0 \to \infty$); may be determined **analytically**.

Bit Error Probability

$\Longrightarrow$ BEP for bit b_{1k}:

$$P_{\mathrm{b1}}[k] \;=\; \mathrm{Q}\left(\sqrt{2\,\frac{d^2_{\mathrm{Im}}[k]}{\left(|h_1|^2+|h_2|^2\right)}\,\frac{E_s}{N_{\mathrm{o}}}}\right)$$

if $\mathrm{Im}\{x[k]\}$ and $\mathrm{Im}\{z[k]\}$ have equal signs

$$P_{\mathrm{b1}}[k] \;=\; 1 \;-\; \mathrm{Q}\left(\sqrt{2\,\frac{d^2_{\mathrm{Im}}[k]}{\left(|h_1|^2+|h_2|^2\right)}\,\frac{E_s}{N_{\mathrm{o}}}}\right)$$

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$\Longrightarrow$ **Overall average BEP** given blocks of L_{B} QPSK symbols:

$$\bar{P}_{\mathrm{b}} \;=\; \frac{1}{2L_{\mathrm{B}}}\sum_{k=0}^{L_{\mathrm{B}}-1} \mathrm{E}\left\{P_{\mathrm{b1}}[k]\right\} + \mathrm{E}\left\{P_{\mathrm{b2}}[k]\right\} \qquad (4)$$

(Expectation is with respect to the channel coefficients h_1 and h_2.)

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- **Simulation Results**
  - Alamouti Detection and ZF/ ML detection
  - Perfect and Non-Perfect Frequency-Offset Estimates
- **Frequency-Offset Estimation**
- **Conclusions**

Simulation Results

- Uncoded transmission, Tx power normalized w.r.t. number of Tx nodes
- QPSK symbols, Gray mapping
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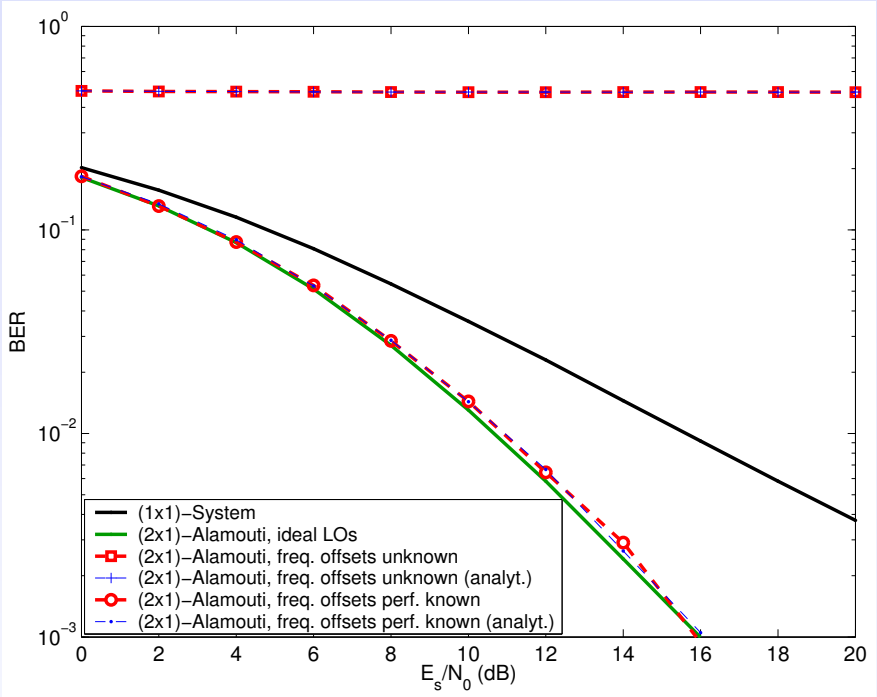

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- Alamouti detection (solid lines) vs. ZF/ ML detection (dashed lines)
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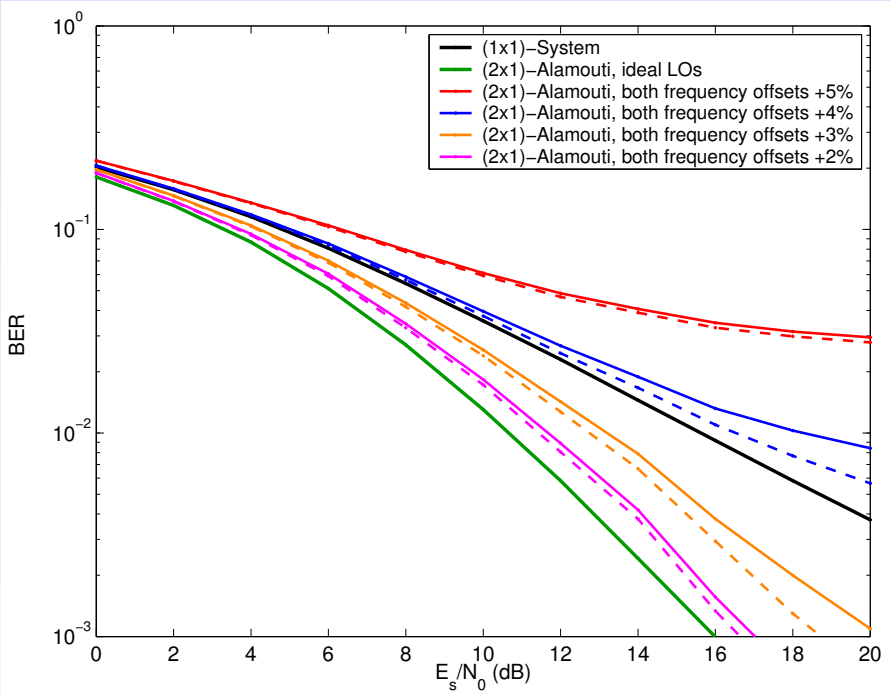

Simulation Results

- ML detection
- $E_s/N_0 = 10$ dB
- Frequency offsets
  $|\zeta_1|, |\zeta_2| \leq 0.04$
- Frequency-offset estimates:
  Absolute errors of 3%

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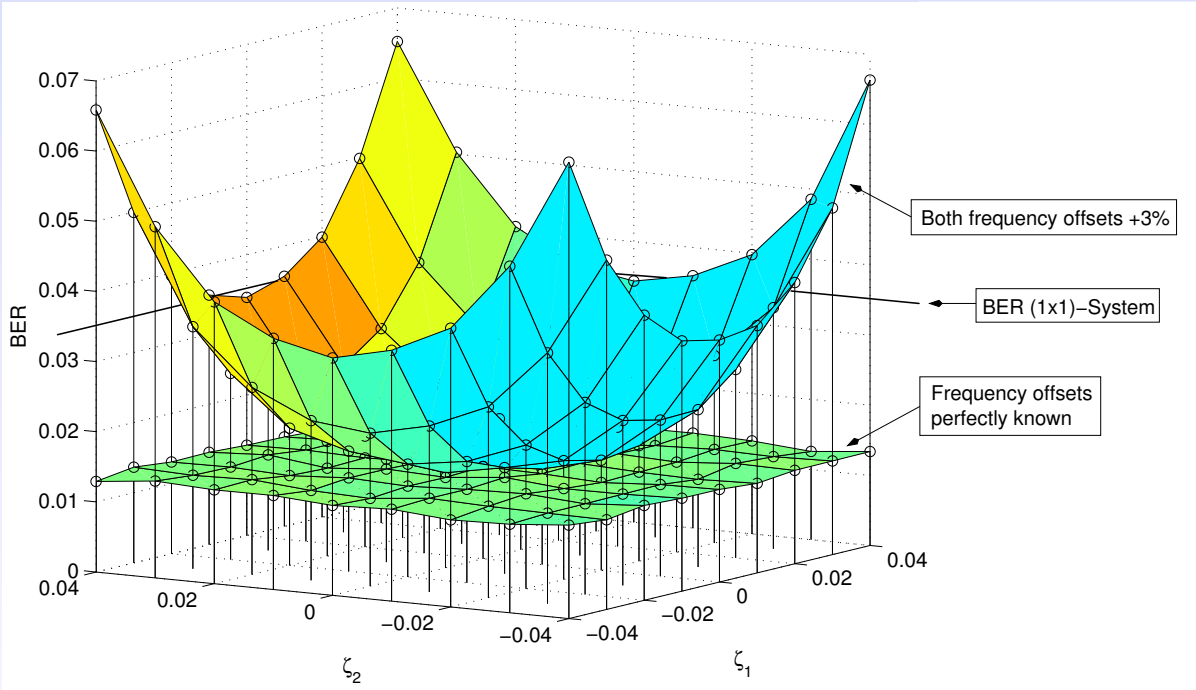

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  - Training-Based Estimation Method
  - Blind Estimation Method
- **Conclusions**

Frequency-Offset Estimation

Training-Based Estimation Method

- Estimating channel coefficients given known data symbols is dual to estimating data symbols given known channel coefficients $\Longrightarrow$ Principle of Alamouti detection can be applied.
- Average over the phase differences of several subsequent channel-coefficient estimates $\Longrightarrow$ Explicit estimates for the frequency-offsets.

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- QPSK symbols: Raise the received samples to the power of four and perform an FFT $\Longrightarrow$ Spectral lines at $4\zeta_1$ and $4\zeta_2$ plus noise.
- Average over several FFTs to eliminate the influence of noise.

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Frequency-offset estimation in cooperating wireless networks is **more difficult** than in (1x1)-systems.

Conclusions

Influence of frequency offsets on the performance of a distributed Alamouti scheme

- Different receiver concepts (Alamouti detection, ZF detection, ML detection)
- Bit error probability given non-ideal local oscillators

$\longrightarrow$ The performance of a distributed Alamouti scheme is very sensitive to frequency offsets.

Frequency-offset estimates

- Accurate frequency-offset estimates are required at the receiver (e.g. error of less than 3%)
- Two different methods for frequency-offset estimation

$\longrightarrow$ Frequency-offset estimation is more difficult than in (1x1)-systems.