Distributed MIMO Systems: Receiver Design and ML Detection

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Introduction and Motivation

- **Co-located MIMO systems**: Transmit antennas use a single oscillator and receiver antennas share a common oscillator. Thus, due to the single CFO, compensation schemes for SISO systems.
- **Distributed MIMO systems**: Transmitters cannot utilize a common oscillator and multiple CFOs and multiple TOs are observed, and thus, compensation schemes for SISO systems cannot be applied.
- **Multiple CFOs**: Different CFOs cause different symbol-energy attenuation on the matched filter output, which hasn't been well studied.
- **Multiple TOs**: Different transmission paths exhibit different propagation delays which implies different TOs at each receive antenna.

System Model

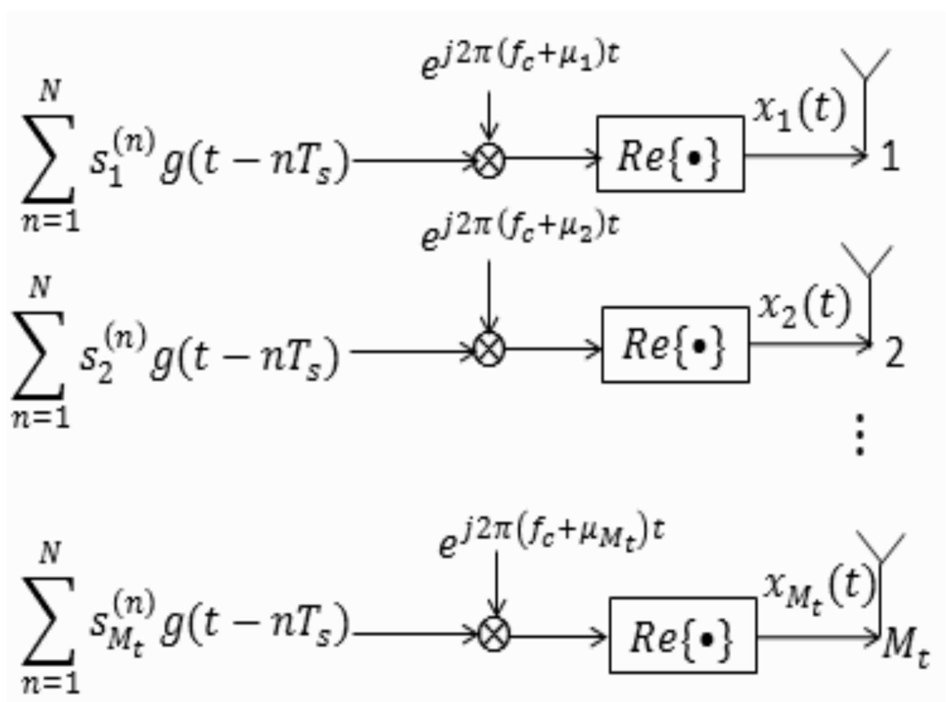

Figure 1 Transmitter processing diagram.

- Distributed MIMO system: M_t Tx and M_r Rx;
- $s_i^{(n)}$: symbol sent by ith Tx at nth time slot;
- $g(t)$: pulse shaping;
- T_s: symbol duration;
- f_c: target carrier frequency;
- μ_i: carrier frequency drift of ith Tx.

The lowpass equivalent signal at the jth Rx:noise.

$$r_j(t) = \frac{1}{2}\sum_{i=1}^{M_t}\sum_{n=1}^{N} h_{i,j} e^{-j2\pi(f_c+\mu_i)\tau_{i,j}} e^{j2\pi\Delta f_{i,j}t} s_i^{(n)} \times g\big(t - nT_s - \tau_{i,j}\big) + n_j(t).$$

- $h_{i,j}$: channel coefficient from ith Tx to jth Rx;
- $\tau_{i,j}$: propagation delay between ith Tx and jth Rx;
- $\Delta f_{i,j}$: CFO between ith Tx and jth Rx;
- $n_j(t)$: lowpass noise.

Proposed Receiver structure and Optimal Detection

Proposed receiver structure:

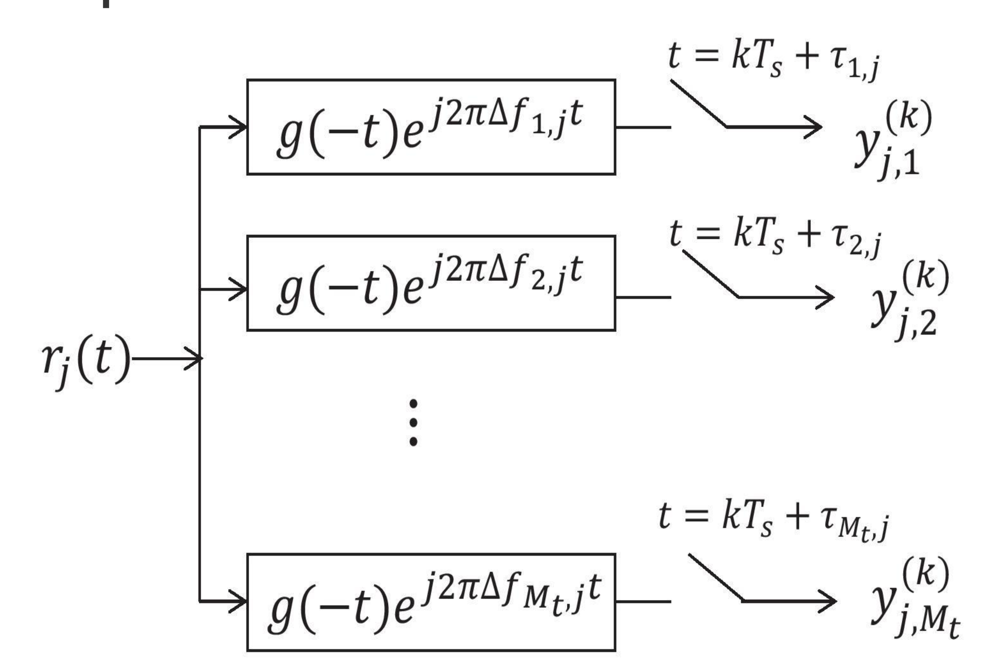

Figure 2 Proposed receiver structure at each receiver antenna

The discrete sample output from the mth branch matched filter with sampling at $t = kT_s + \tau_{m,j}$:

$$y_{j,m}{}^{(k)} = \frac{1}{2}\sum_{i=1}^{M_t}\sum_{n=1}^{N} \tilde{h}_{i,j} e^{j2\pi\Delta f_{i,j}(kT_s+\tau_{m,j})} s_i{}^{(n)} G_{i,j,m,k-n} + N_{j,m}{}^{(k)}.$$

- $\tilde{h}_{i,j} \triangleq h_{i,j} e^{-j2\pi(f_c+\mu_i)\tau_{i,j}}$;
- $G_{i,j,m,p} \triangleq \int_{-\infty}^{+\infty} g\big(pT_s + \tau_{m,j} - \tau_{i,j}\big)\, g(-\tau) \times e^{j2\pi(\Delta f_{m,j}-\Delta f_{i,j})\tau} d\tau$;
- $N_{j,m}{}^{(k)} = \{n_j(t)\} * \{g(-t)e^{j2\pi\Delta f_{m,j}t}\}\big|_{t=kT_s+\tau_{m,j}}$;

<u>Note:</u> When $i = m$, and $p = 0$,

$$G_{i,j,m,p} = \int_{-\infty}^{+\infty} g^2(-\tau)\, d\tau;$$

We consider pulse shape within one symbol duration and the difference of the TOs is within one symbol duration.

Compact expression of $y_{j,m}{}^{(k)}$:

$$y_{j,m}{}^{(k)} = \psi_{j,m}{}^{(k)} \boldsymbol{S}^T + N_{j,m}{}^{(k)},$$

$$\boldsymbol{S} = \left[\boldsymbol{s}^{(k-1)^T}, \boldsymbol{s}^{(k)^T}, \boldsymbol{s}^{(k+1)^T}\right], \boldsymbol{s}^{(k)} = \left[s_1{}^{(k)}, \cdots, s_{M_t}{}^{(k)}\right]^T,$$

$$\psi_{j,m}^{(k)} \triangleq \frac{1}{2}\begin{bmatrix} \tilde{h}_{1,j}e^{j2\pi\Delta f_{1,j}(kT_s+\tau_{m,j})}G_{1,j,m,1} \\ \vdots \\ \tilde{h}_{M_t,j}e^{j2\pi\Delta f_{M_t,j}(kT_s+\tau_{m,j})}G_{M_t,j,m,1} \\ \tilde{h}_{1,j}e^{j2\pi\Delta f_{1,j}(kT_s+\tau_{m,j})}G_{1,j,m,0} \\ \vdots \\ \tilde{h}_{M_t,j}e^{j2\pi\Delta f_{M_t,j}(kT_s+\tau_{m,j})}G_{M_t,j,m,0} \\ \tilde{h}_{1,j}e^{j2\pi\Delta f_{1,j}(kT_s+\tau_{m,j})}G_{1,j,m,-1} \\ \vdots \\ \tilde{h}_{M_t,j}e^{j2\pi\Delta f_{M_t,j}(kT_s+\tau_{m,j})}G_{M_t,j,m,-1} \end{bmatrix}^T$$

Received signal at the jth receiver:

$$\boldsymbol{Y}_j{}^{(k)} = [y_{j,1}{}^{(k)}, \cdots, y_{j,M_t}{}^{(k)}]^T = \psi_j{}^{(k)}\boldsymbol{S}^T + \boldsymbol{N}_j{}^{(k)},$$

where $\psi_j{}^{(k)} = [\psi_{j,1}{}^{(k)^T} \cdots \psi_{j,M_t}{}^{(k)^T}]^T$,

$\boldsymbol{N}_j{}^{(k)} = [N_{j,1}{}^{(k)}, \cdots, N_{j,M_t}{}^{(k)}]^T$.

Overall received signal:

$$\boldsymbol{Y}^{(k)} = [\boldsymbol{Y}_1{}^{(k)^T} \cdots \boldsymbol{Y}_{M_r}{}^{(k)^T}]^T = \Psi^{(k)}\boldsymbol{S}^T + \boldsymbol{N}^{(k)},$$

where $\Psi^{(k)} = [\psi_1{}^{(k)^T} \cdots \psi_{M_r}{}^{(k)^T}]^T$,

$\boldsymbol{N}^{(k)} = [\boldsymbol{N}_1{}^{(k)^T} \cdots \boldsymbol{N}_{M_r}{}^{(k)}]^T$.

Optimal detection (ML):

$$\widehat{\boldsymbol{s}^{(k)}} = \underset{\boldsymbol{s}^{(k-1)}, \boldsymbol{s}^{(k)}, \boldsymbol{s}^{(k+1)}}{\operatorname{argmax}} P(\boldsymbol{Y}^{(k)})$$

where

$$P(\boldsymbol{Y}^{(k)}) = \frac{1}{(2\pi)^{\frac{M_t M_r}{2}}|\Sigma|^{\frac{1}{2}}} exp\left\{ -\frac{1}{2}\left(\boldsymbol{Y}^{(k)} - \Psi^{(k)}\boldsymbol{S}^T\right)^H \times \Sigma^{-1}\left(\boldsymbol{Y}^{(k)} - \Psi^{(k)}\boldsymbol{S}^T\right)\right\}$$

$$\Sigma = \begin{pmatrix} Var(N_{1,1}^{(k)}) & Cov(N_{1,1}^{(k)},N_{1,2}^{(k)}) & \cdots & Cov(N_{1,1}^{(k)},N_{M_r,M_t}^{(k)}) \\ Cov(N_{1,2}^{(k)},N_{1,1}^{(k)}) & Var(N_{1,2}^{(k)}) & \cdots & Cov(N_{1,2}^{(k)},N_{M_r,M_t}^{(k)}) \\ \vdots & \vdots & \ddots & \vdots \\ Cov(N_{M_r,M_t}^{(k)},N_{1,1}^{(k)}) & Cov(N_{M_r,M_t}^{(k)},N_{1,2}^{(k)}) & \cdots & Var(N_{M_r,M_t}^{(k)}) \end{pmatrix}$$

$$Var(N_{j,m}^{(k)}) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} R_n(\tau-\lambda)g(-\tau)g(-\lambda) \times e^{j2\pi\Delta f_{m,j}(\tau-\lambda)}\, d\tau\, d\lambda,$$

$$Cov(N_{j,m}^{(k)}, N_{j',m'}^{(k)}) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} R_n(\tau_{m,j} - \tau_{m',j'} + \tau - \lambda) \times g(-\tau)g(-\lambda)e^{j2\pi(\Delta f_{m,j}\tau - \Delta f_{m',j'}\lambda)}\, d\tau\, d\lambda.$$

Simulation Results

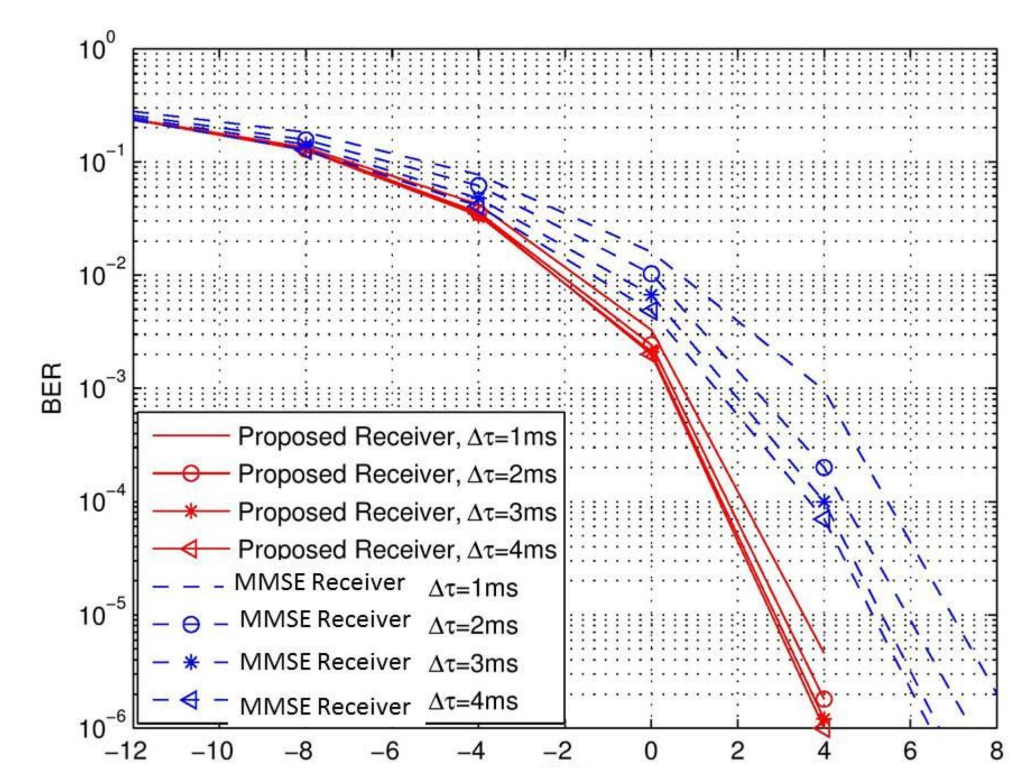

Figure 3(a) Performances of the proposed receiver and receiver in[2] with multiple TOs but without multiple CFOs.

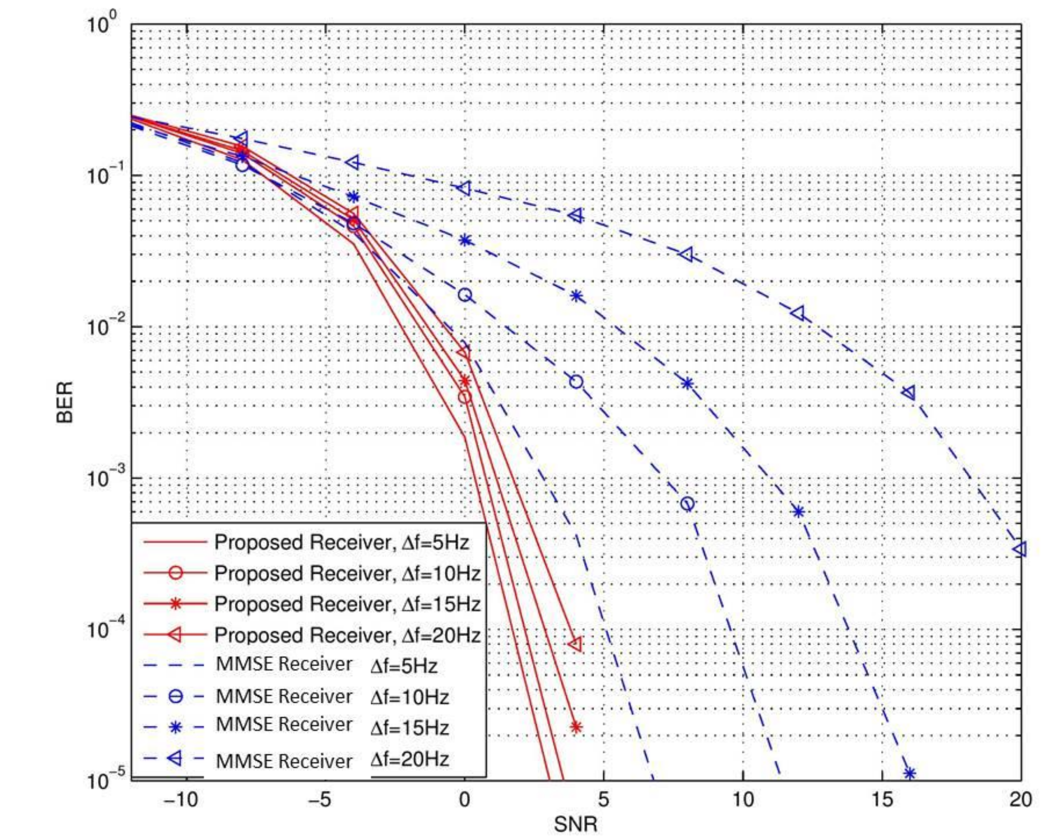

Figure 3(b) Performances of the proposed receiver and receiver in[2] with multiple CFOs but without multiple TOs.

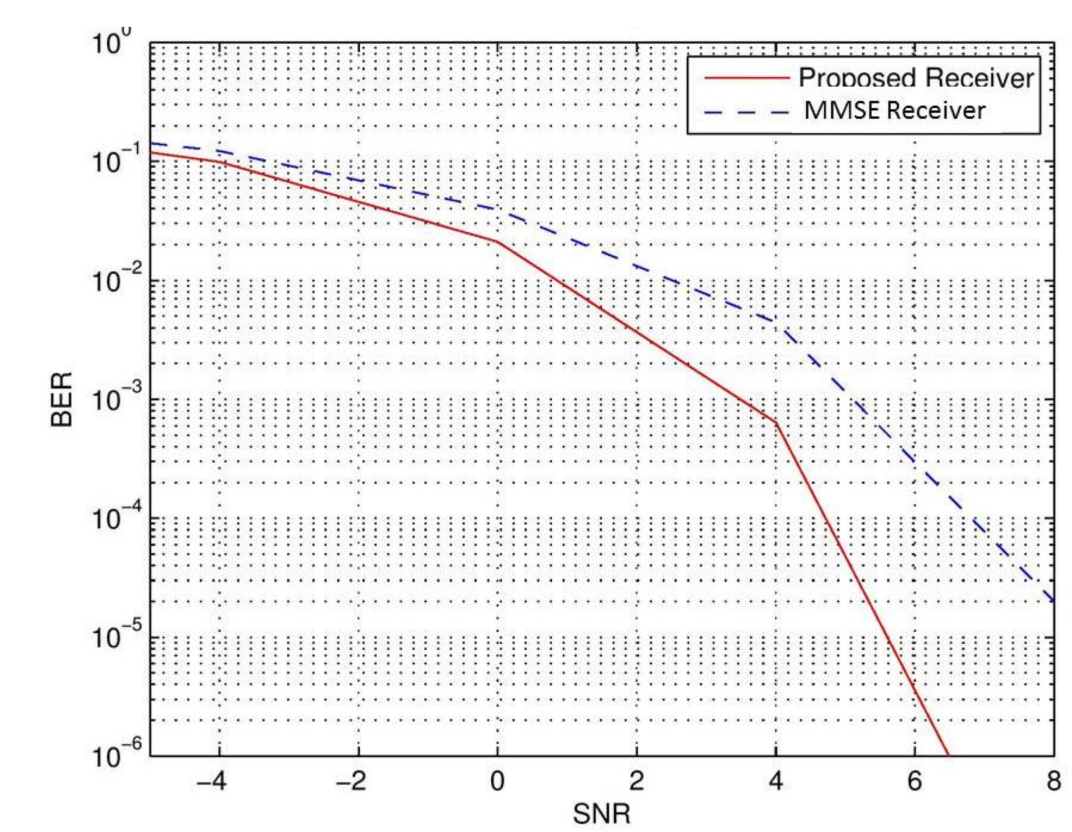

Figure 4 Performances of the proposed receiver and receiver in[2] with both multiple CFOs and multiple TOs in system with Mt=2 distributed transmit antennas.

<u>Note:</u> In the simulation setup, we apply a root-raised cosine filter with a roll-off factor of 0.5 and symbol duration is set to Ts=10 ms. BPSK signaling is used and channel coefficients are assumed to be quasi-static during the transmission of a symbol sequence. In Figure 4, CFOs are set to +15 Hz and -15 Hz and TO is set to be 4 ms.

Conclusion

We proposed a novel receiver design for distributed MIMO systems that accounts for multiple CFOs and multiple TOs. The proposed structure utilizes a bank of pulse matched filters (one per effective CFO) at each receive antenna, followed by ML information symbol detector. Each filter in the bank is sampled at the symbol rate with sampling timing selected according to the corresponding TO. For the proposed receiver configuration, we derive the ML detector. Simulation results show that the proposed receiver structure together with the optimal ML detection offers significant performance gains in presence of multiple CFOs and multiple TOs.