Asynchronous Interference Mitigation in Cooperative Base Station Systems

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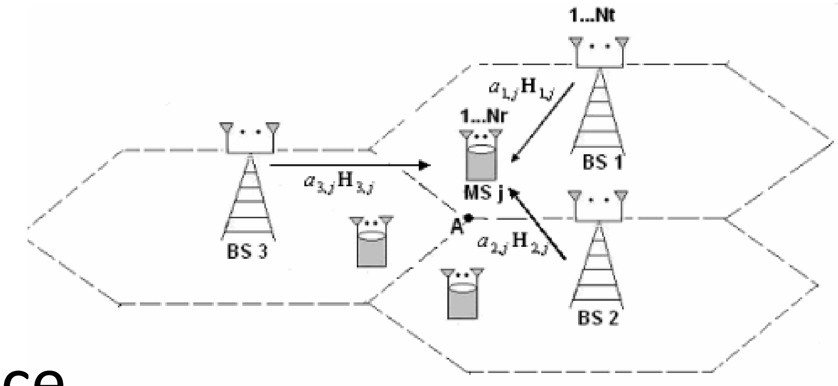
Abstract

- Previous papers have generally assumed perfect synchronization between base stations and mobile users
- Intuitively it is clear to see that the system will have timing issues and is fundamentally asynchronous
- Develop a model for the asynchronicity
- Develop algorithms that are better than existing ones at mitigating asynchronous impact
- Discuss realities of asynchronous systems, not just interference

Background

- While MIMO has significant efficiency gains in point-to-point communications, its use in cellular systems is limited by inter-cell co-channel interference



  - This is commonly reduced via power control, frequency, reuse, and spreading codes
- Base station cooperation can significantly improve spectral efficiency
  - With the right assumptions, cooperating base stations can be seen as a single base station with spatially diverse antennas

Intuitions

- Perfect timing-advance ensures signals from base stations reach their intended recipients synchronously
- Base stations cannot also align all the interfering signals at each other mobile station because of the different propagation times
- Simultaneous arrival of desired and interfering signals is unrealistic

Multiple Ways Exist to Implement

- Dirty Paper Coding
- Tomlinson-Harashima precoding
- Multi-user dection in mobile handsets
- ALL TOO COMPLICATED
- Focus on linear precoding designs
  - Lower complexity at BSs and MSs
  - Mitigate inter-cell interference
  - Exploit macro-diversity
  - Can avoid capacity bottlenecks

Methods to Find Optimal Linear Precoding Matrices

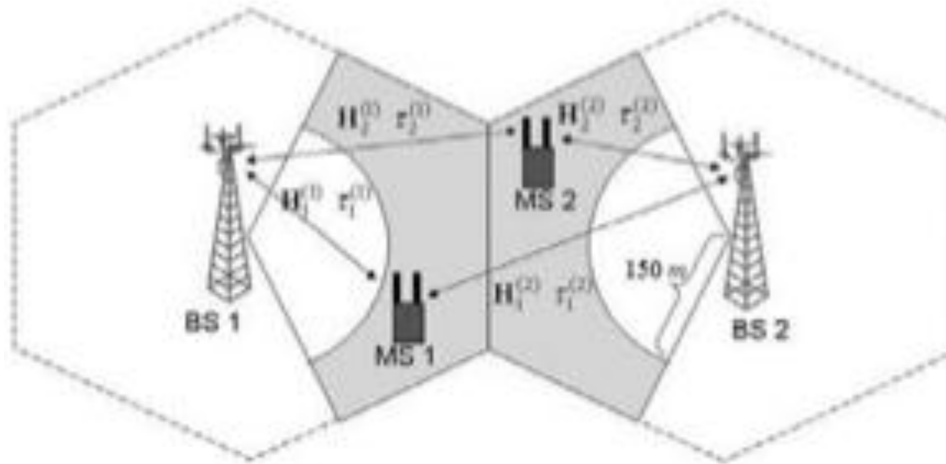
- Minimizing the Mean Square Error (MSE)
- Maximizing the Signal to Leakage and Noise Ratio (SLNR)
- Maximizing the Sum Rate
  - Arguably the ultimate metric that determines spectrum utilization

System Model

- B stations, each with N_T antennas
- K users, each with N_R antennas
- Total of L_k data streams to user k
- $H_k^{(b)}$ is matrix to user k from base station b
  - $H_k = [H_k^{(1)} \ldots H_k^{(B)}]$
- Data signal $s_k(m)$ is precoded by matrix $T_k^{(b)}$
  - $x_k^{(b)}(m) = T_k^{(b)} s_k(m)$
  - $x_k(m) = [x_k^{(1)}(m)^T \ldots x_k^{(B)}(m)^T]^T$

Asynchronous Interference Despite Perfect Synchronization

- CSI at each base station includes propagation delay from each BS to each user
- $\tau_k^{(b)}$ delay from b to k
- $\Delta\tau_k^{(b)} = \tau_k^{(b)} - \tau_k^{(b_k)}$
  - b_k is the closest BS



$$\mathbf{r}_k(t) = \sum_{m=0}^{\infty} g(t - mT_S - \tau_k^{(b_k)})\mathbf{H}_k\mathbf{x}_k(m) + \mathbf{n}_k(t)$$

$$+\sum_{m=0}^{\infty}\left\{\sum_{\substack{j=1\\(j\neq k)}}^{K}\sum_{b=1}^{B} g(t - mT_S - \tau_k^{(b)} + \Delta\tau_j^{(b)})\mathbf{H}_k^{(b)}\mathbf{x}_j^{(b)}(m)\right\}$$

Sufficient Statistic

- $r_k(t)$ passed through matched filter

$$\mathbf{y}_k(m) = \mathbf{H}_k \mathbf{T}_k \mathbf{s}_k(m) + \sum_{\substack{j=1 \\ (j \neq k)}}^{K} \sum_{b=1}^{B} \mathbf{H}_k^{(b)} \mathbf{T}_j^{(b)} \mathbf{i}_{jk}^{(b)}(m) + \mathbf{n}_k(m)$$

- $i_{jk}^{(b)}(m)$ = interference at k from b for user j
  - Depends on $\tau_{jk}^{(b)} = (\tau_k^{(b)} - \Delta\tau_j^{(b)}) - \tau_k^{(b_k)} = \Delta\tau_k^{(b)} - \Delta\tau_j^{(b)}$.

$$\mathbf{i}_{jk}^{(b)}(m) = \rho(\delta_{jk}^{(b)} - T_S)\mathbf{s}_j(m_{jk}^{(b)}) + \rho(\delta_{jk}^{(b)})\mathbf{s}_j(m_{jk}^{(b)} + 1).$$

where $\rho(\tau) = \int_0^{T_S} g(t)g(t-\tau)dt$ with $\rho(0) = 1$ and $\delta_{jk}^{(b)} = \tau_{jk}^{(b)} \mod T_S$

How is this different?

- This model $$\mathbf{y}_k(m) = \mathbf{H}_k\mathbf{T}_k\mathbf{s}_k(m) + \sum_{\substack{j=1 \\ (j\neq k)}}^{K}\sum_{b=1}^{B}\mathbf{H}_k^{(b)}\mathbf{T}_j^{(b)}\mathbf{i}_{jk}^{(b)}(m) + \mathbf{n}_k(m)$$
- Previous models $$\mathbf{y}_k(m) = \mathbf{H}_k\mathbf{T}_k\mathbf{s}_k(m) + \sum_{\substack{j=1 \\ (j\neq k)}}^{K}\left(\sum_{b=1}^{B}\mathbf{H}_k^{(b)}\mathbf{T}_j^{(b)}\right)\mathbf{s}_j(m) + \mathbf{n}_k(m),$$ $$= \mathbf{H}_k\mathbf{T}_k\mathbf{s}_k(m) + \sum_{\substack{j=1 \\ (j\neq k)}}^{K}\mathbf{H}_k\mathbf{T}_j\mathbf{s}_j(m) + \mathbf{n}_k(m). \quad (5)$$
- We can clearly see these models assume $i_{jk}^{(b)}(m) = s_j(m)$ instead of our value of $$\mathbf{i}_{jk}^{(b)}(m) = \rho(\delta_{jk}^{(b)} - T_S)\mathbf{s}_j(m_{jk}^{(b)}) + \rho(\delta_{jk}^{(b)})\mathbf{s}_j(m_{jk}^{(b)} + 1).$$
- Oversimplified model is less useful

Normalized Mean Square Error (MSE)

- Goal is to optimize precoders $\{T_k\}$ to minimize overall MSE between received signal and "desired" signal
  - "Desired" signal z_k mimics single user MIMO channel
    - Determined via eigen-BF matrix with water-filling power

$$\{\mathbf{T}_k^{\mathrm{opt}}\}_{k=1}^{K} = \arg \min_{\{\mathbf{T}_k\}_{k=1}^{K}} \sum_{k=1}^{K} \frac{\mathbb{E}\left[\|\mathbf{y}_k - \mathbf{z}_k\|^2\right]}{\Omega_k} \qquad \Omega_k = \mathbb{E}\left[\mathrm{Tr}\left\{\mathbf{z}_k \mathbf{z}_k^\dagger\right\}\right]$$

- Closed form solution $\mathbf{T}_k = \frac{1}{\Omega_k}\left[\mathbf{C}_k + \kappa_k \mathbf{I}_{N_T B}\right]^{-1} \mathbf{H}_k^\dagger \mathbf{A}_k$

with $\mathbf{A}_k = \mathbf{H}_k \mathbf{V}_k$ and $\mathbf{C}_k = \begin{bmatrix} \mathbf{C}_k^{(1,1)} & \mathbf{C}_k^{(1,2)} & \cdots & \mathbf{C}_k^{(1,B)} \\ \mathbf{C}_k^{(2,1)} & \mathbf{C}_k^{(2,2)} & \cdots & \mathbf{C}_k^{(2,B)} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C}_k^{(B,1)} & \mathbf{C}_k^{(B,2)} & \cdots & \mathbf{C}_k^{(B,B)} \end{bmatrix}$ and $\mathbf{C}_k^{(b_1,b_2)} = \sum_{j=1}^{K} \frac{\beta_{kj}^{(b_1,b_2)}}{\Omega_j} \mathbf{H}_j^{(b_1)\dagger} \mathbf{H}_j^{(b_2)}$

Maximize SLNR

- Design precoding matrices to maximize SLNR
  - Limit to scaled unitary matrices $\mathbf{T}_k = \sqrt{\frac{P_k^{\mathrm{tx}}}{L_k}}\mathbf{Q}_k$
    - Makes optimization analytically feasible
- Optimization problem $\mathbf{Q}_k^{\mathrm{opt}} = \arg\max_{\mathbf{Q}_k} \mathrm{SLNR}_k, \quad 1 \le k \le K.$
- This results in the problem $\mathbf{Q}_k^{\mathrm{opt}} = \arg \max_{\mathbf{Q}_k:\ \mathbf{Q}_k^{\dagger}\mathbf{Q}_k = \mathbf{I}_{L_k}} \min_{l=1,\dots,L} \frac{\mathbf{q}_{kl}^{\dagger}\mathbf{M}_k\mathbf{q}_{kl}}{\mathbf{q}_{kl}^{\dagger}\mathbf{N}_k\mathbf{q}_{kl}}$
- Which is solved by $\mathbf{q}_{kl}^{\mathrm{opt}} = \mathbf{v}_l(\mathbf{N}_k^{-1}\mathbf{M}_k),\ \text{for } 1 \le l \le L_k$
  - Which are the eigenvectors of $N_k^{-1}M_k$
    - I was unable to determine a meaning for N_k
    - M_k is a scaled version of $(H_k^+)(H_k)$

Maximize Sum Rate

- Strive to maximize the sum rate over all users

$$\{\mathbf{T}_k^{\text{opt}}\}_{k=1}^{K} = \arg \max_{\{\mathbf{T}_k\}_{k=1}^{K}} \sum_{k=1}^{K} R_k,$$
$$\text{s. t.} \quad \text{Tr}\left\{\mathbf{T}_k^\dagger \mathbf{T}_k\right\} \leq P_k^{\text{tx}}, \quad \text{for } k = 1, \ldots, K.$$

- Rate given by $R_k = \log\left|\mathbf{I}_{N_R} + \mathbf{\Phi}_k^{-1}\mathbf{H}_k\mathbf{T}_k\mathbf{T}_k^\dagger\mathbf{H}_k^\dagger\right|$
  - Φ_k is the covariance of (noise + interference)
- Non-linear and non-convex problem
- Iterative optimization technique
  - Optimize T_k by keeping $T_{j\neq k}$ fixed
  - Continue optimizing until sum rate increases by less than a certain threshold

Imperfect Timing-Advance

- Inevitable due to imperfect delay estimation, moving users, and synchronization errors
- Users are unaware of timing errors and so decode the signal as if it is synchronized
- Degrades performance in 3 ways
  – Power degradation term
  – Additional ISI term
  – Imperfect knowledge of interference correlation

Conclusion

- Paper moves a step closer to realizing base station cooperation
- This paper focused on single-carrier communication with flat fading channels
  - More work can be done looking at OFDM systems