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 detection 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 $b$
  
  $\quad H_k = [H_k^{(1)} \ldots H_k^{(B)}]$
• Data signal $s_k(m)$ is precoded by matrix $T_k^{(b)}$
  
  $\quad x_k^{(b)}(m) = T_k^{(b)}s_k(m)$
  $\quad x_k(m) = [x_k^{(1)}(m)^\top \ldots x_k^{(B)}(m)^\top]^\top$
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

\[
r_k(t) = \sum_{m=0}^{\infty} g(t - mT_S - \tau_k^{(b_k)}) \mathbf{H}_k \mathbf{x}_k(m) + n_k(t) + \sum_{m=0}^{\infty} \sum_{j=1}^{K} \sum_{b=1}^{B} g(t - mT_S - \tau_k^{(b)} + \Delta \tau_j^{(b)}) \mathbf{H}_k^{(b)} \mathbf{x}_j^{(b)}(m)\]
Sufficient Statistic

• $r_k(t)$ passed through matched filter

\[ y_k(m) = H_k T_k s_k(m) + \sum_{j=1}^{K} \sum_{b=1}^{B} H_k^{(b)} T_j^{(b)} i_{jk}^{(b)}(m) + n_k(m) \]

• $i_{jk}^{(b)}(m) =$ interference at $k$ from $b$ for user $j$
  
  – Depends on

\[ \tau_{jk}^{(b)} = (\tau_k^{(b)} - \Delta \tau_j^{(b)}) - \tau_{bk}^{(b)} = \Delta \tau_k^{(b)} - \Delta \tau_j^{(b)} \]

\[ i_{jk}^{(b)}(m) = \rho(\delta_{jk}^{(b)} - T_S) s_j(m_{jk}^{(b)}) + \rho(\delta_{jk}^{(b)}) s_j(m_{jk}^{(b)} + 1). \]

where

\[ \rho(\tau) = \int_0^{T_S} g(t)g(t-\tau)dt \text{ with } \rho(0) = 1 \quad \text{and} \quad \delta_{jk}^{(b)} = \tau_{jk}^{(b)} \mod T_S \]
How is this different?

• This model
  \[ y_k(m) = H_k T_k s_k(m) + \sum_{j=1}^{K} \sum_{b=1}^{B} H_k^{(b)} T_j^{(b)} i_{jk}^{(b)}(m) + n_k(m), \]

• Previous models
  \[ y_k(m) = H_k T_k s_k(m) + \sum_{j=1}^{K} \left( \sum_{b=1}^{B} H_k^{(b)} T_j^{(b)} \right) s_j(m) + n_k(m), \]
  
  \[ = H_k T_k s_k(m) + \sum_{j=1}^{K} H_k T_j s_j(m) + n_k(m). \quad (5) \]

• We can clearly see these models assume \( i_{jk}^{(b)}(m) = s_j(m) \) instead of our value of
  \[ i_{jk}^{(b)}(m) = \rho(\delta_{jk}^{(b)} - T_S) s_j(m_{jk}^{(b)}) + \rho(\delta_{jk}^{(b)}) s_j(m_{jk}^{(b)} + 1). \]

• 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

\[
\{T_k^{\text{opt}}\}_{k=1}^{K} = \arg \min_{\{T_k\}_{k=1}^{K}} \sum_{k=1}^{K} \frac{\mathbb{E}[\|y_k - z_k\|^2]}{\Omega_k} \quad \Omega_k = \mathbb{E}\left[\text{Tr}\left\{z_k z_k^\dagger\right\}\right].
\]

• Closed form solution

\[
T_k = \frac{1}{\Omega_k} \left[ C_k + \kappa_k I_{N_R B} \right]^{-1} H_k^\dagger A_k
\]

with

\[
A_k = H_k V_k \quad \text{and} \quad C_k = \begin{bmatrix}
  C_k^{(1,1)} & C_k^{(1,2)} & \cdots & C_k^{(1,B)} \\
  C_k^{(2,1)} & C_k^{(2,2)} & \cdots & C_k^{(2,B)} \\
  \vdots & \vdots & \ddots & \vdots \\
  C_k^{(B,1)} & C_k^{(B,2)} & \cdots & C_k^{(B,B)}
\end{bmatrix}
\]

and

\[
C_k^{(b_1,b_2)} = \sum_{j=1}^{K} \frac{\beta_{kj}^{(b_1,b_2)}}{\Omega_j} H_j^{(b_1)} H_j^{(b_2)}
\]
Maximize SLNR

• Design precoding matrices to maximize SLNR
  – Limit to scaled unitary matrices
    • Makes optimization analytically feasible

• Optimization problem

• This results in the problem

• Which is solved by
  – 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

- Rate given by
  \[ R_k = \log \left| I_{N_k} + \Phi_k^{-1} H_k T_k T_k^\dagger H_k^\dagger \right| \]
  - \( \Phi_k \) 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

The optimization problem is:
\[ \{ T_k^{\text{opt}} \}_{k=1}^K = \arg \max_{\{ T_k \}_{k=1}^K} \sum_{k=1}^K R_k, \]
subject to
\[ \text{Tr} \left\{ T_k^\dagger T_k \right\} \leq P_k^t \quad \text{for} \quad k = 1, \ldots, K. \]
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