CENTRE FOR WIRELESS COMMUNICATIONS
University of Oulu

Wireless Information Theory Summer School
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Energy Efficiency of Future Networks
Part 1:

Energy Efficient Transmission in Classical Wireless Networks

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Goals

- Energy Efficiency: What it meant last decade; what it means today
- From a communication network design perspective what should we care about for energy efficient design of
  - cellular/conventional wireless networks? (greenish)
  - rechargeable (energy harvesting) networks? (green)

Prerequisites

- Optimization (Basic)
- Communication Theory (Basic)
- Information Theory (Basic)
- Fairly self-contained otherwise

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Outline

- Morning Session 1; Yener: Energy Efficiency- Classical Networks Part 1
- Morning Session 2; Ulukus: Energy Efficiency- Classical Networks Part 2
- Afternoon Session 1; Yener: Energy Efficiency- Rechargeable Networks Part 1
- Afternoon Session 1; Ulukus: Energy Efficiency- Rechargeable Networks Part 2

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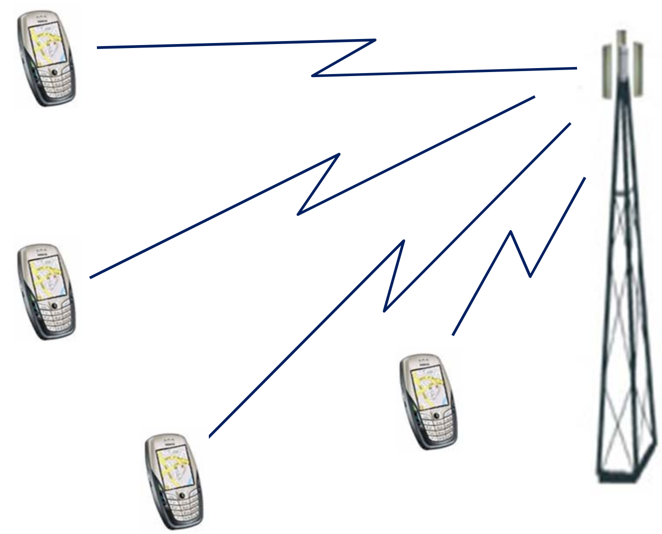
"Classical" Networks



- Multiple User/shared frequency resources (interference limited)
- Battery powered mobile nodes
- **Single charge**

Applications

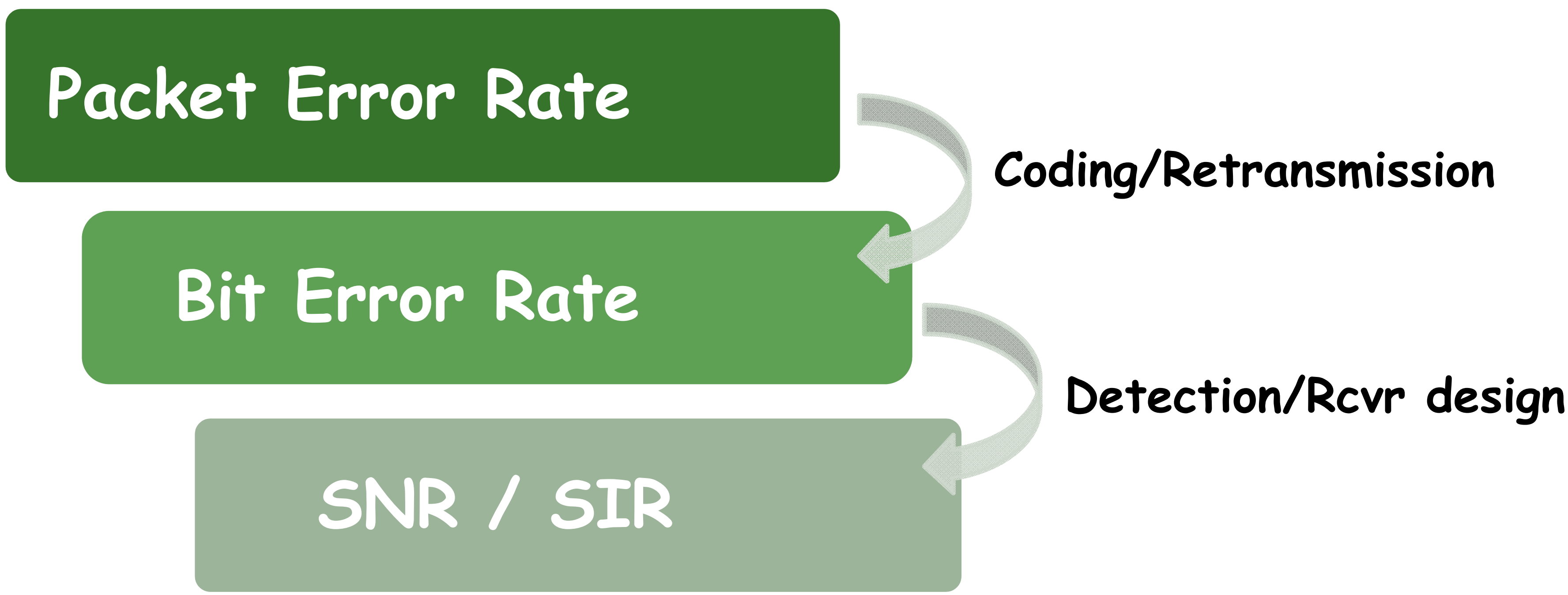
- Cellular Networks (nG, n>1) including multi-tier (femto+macro) & network MIMO
- Sensor networks (shared bandwidth, single or multiple "sinks"
- Adhoc networks with "access" points
- Multimedia traffic, we will concentrate on the portion that is "energy hungry" = delay intolerant

Performance Measure

Quality of Service (QoS)

- Delay sensitive applications (e.g. voice)
- **Packet error rate – a maximum tolerable error rate guarantees a reliable connection**

Performance Measure



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Performance Measure

Signal-to-Interference Ratio (SIR)

$$SIR_i = \frac{p_i h_i}{\sum_{j \neq i} \alpha_{ij} p_j h_j + \sigma}$$

p_j : transmit power of user j

h_j : channel coefficient for user j

α_{ij} : interference of user j on user i

σ : noise power at receiver

$$PER \leq targetPER$$

$$\leftrightarrow BER \leq targetBER$$

$$\leftrightarrow SIR \geq targetSIR$$

Energy Efficiency?

- From the communication theory (PHY) perspective = Transmission energy dominant
- Communication carried in sessions (consists of frames consists of packets)
- Energy spent= duration*power

(for whatever time scale you care to keep power constant)

Energy Efficient TX

Mimimize total energy subject to QoS requirement ≡ Minimize total power subject to minimum SIR req. for all users

$$\min_{\vec{P},\vec{\alpha}} \sum_{i=1}^{N} p_i$$

$$SIR_i \geq \gamma_i \quad i = 1, \ldots, N$$

$$\vec{P} \geq 0$$

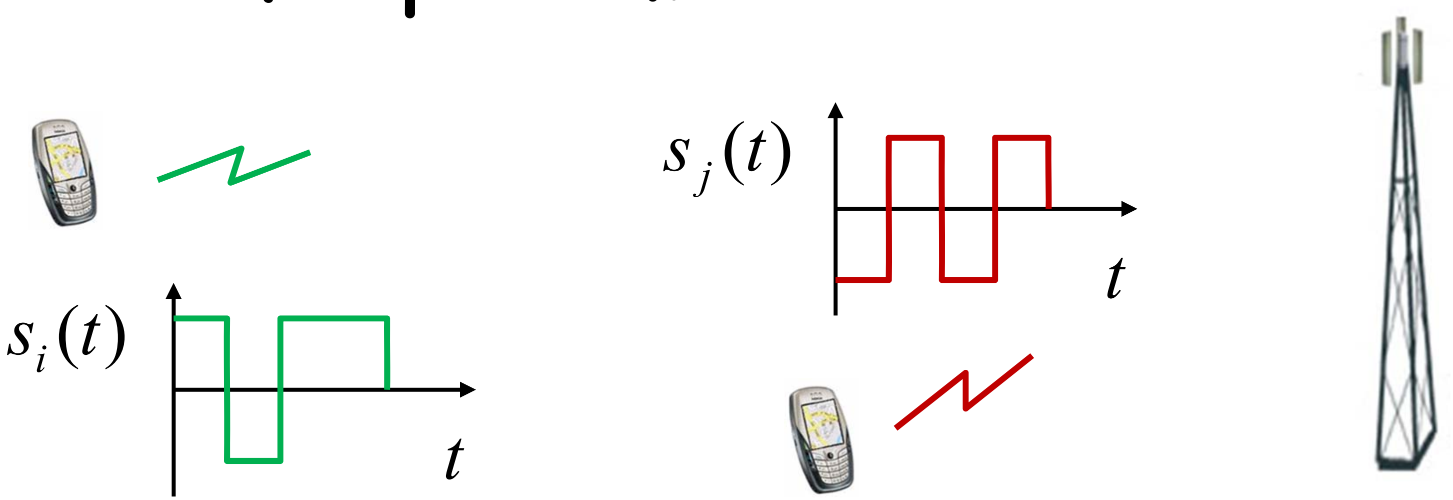
Energy Efficient TX

$$\frac{p_i h_i}{\sum_{j \neq i} \alpha_{ij} p_j h_j + \sigma} \geq \gamma_i \Leftrightarrow p_i \geq \gamma_i \left(\frac{\sum_{j \neq i} \alpha_{ij} p_j h_j + \sigma}{h_i} \right)$$

- The larger the interference a user experiences, the large transmit power it has to expend to overcome it.
- **Bottomline:** Minimizing transmit power amounts to managing interference.

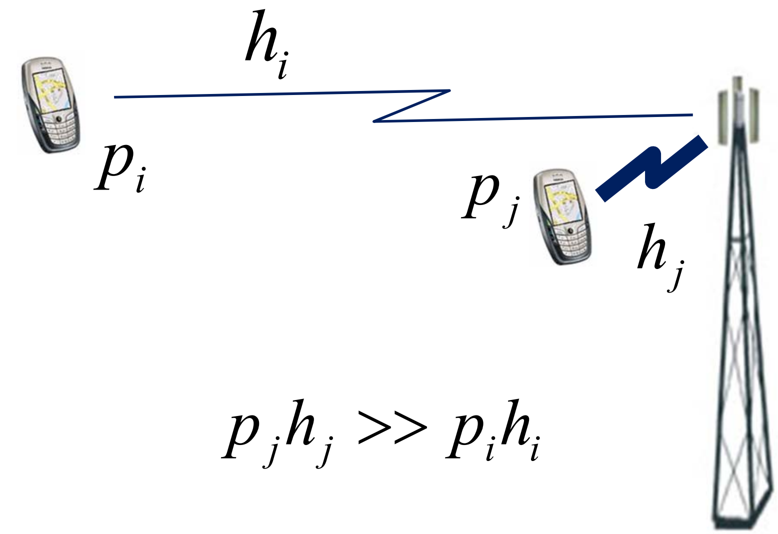
Interference Management for CDMA/SDMA systems

- Users have unique, but **non-orthogonal** signatures (CDMA: temporal; SDMA: spatial)
- **Near-far problem**



Near-Far Problem

- Strong user can destroy weak user's communication

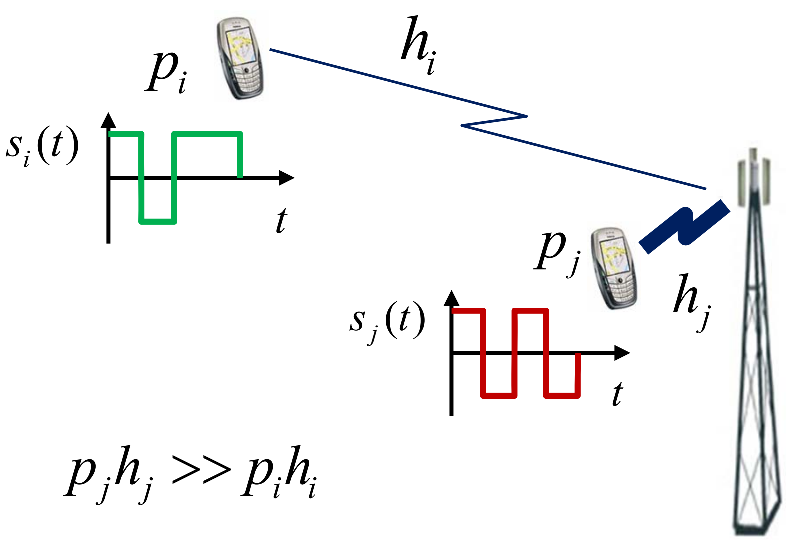


- Prominent in CDMA/SDMA systems

(users share the same frequency and time)

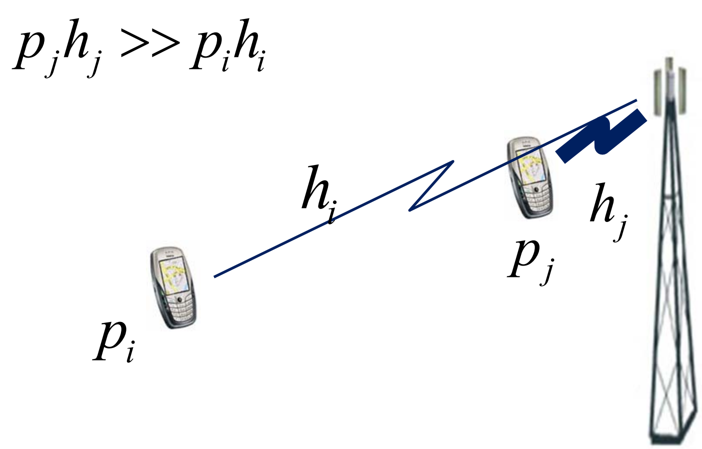
Near-Far Problem

CDMA



Better user with close code $s(t)$ interferes

SDMA



Better user with close spatial position interferes

Interference Management Techniques

- Power Control (any system)
- Multiuser Detection/Interference Cancellation (wideband)
- Receiver Beamforming/adaptive sectorization (multiantenna base station)
- MIMO (multiantenna terminals)

Interference Management Techniques (1995-2001)

- Power Control [Zander 93][Yates 95][Hanly 96]
- Multiuser Detection (Temporal Filtering) [Verdu 84, 89][Madhow, Honig 94]
- Beamforming (Spatial Filtering) [Naguib et. al. 95]
- Multiuser Detection and Beamforming [Yener et.al. 00]
- Power Control and Multiuser Detection [Ulukus, Yates 98]
- Power Control and Beamforming [Rashid-Farrokhi et. al. 98]
- Power Control, Multiuser Detection and Beamforming [Yener et al 01]
- Power Control and Adaptive Cell Sectorization [Saraydar et al 01]

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Power Control [Yates, 1995]

$$\min_{\vec{P},\vec{\alpha}} \sum_{i=1}^{N} p_i$$

$$SIR_i \geq \gamma_i \quad i = 1, \ldots, N$$

$$\vec{P} \geq 0$$

Find power vector **p** that meets SIR requirements ***I(p)*** for each user.

$$p_i \geq I_i(\mathbf{p}) \quad \forall i$$

$$\boldsymbol{p} \geq \boldsymbol{I}(\boldsymbol{p})$$ → Interference function

Power Control

- N users, M base stations

$$SIR = p_j \mu_{kj}(\mathbf{p}) = p_j \cdot \underbrace{\frac{h_{kj}}{\sum_{i \neq j} h_{ki} p_i + \sigma_k}}_{\mu_{kj}(\mathbf{p})}$$

h_{kj} : Gain of user j to base k

p_j : Transmitted power of user j

σ_k : Receiver noise power at base k

Interference Functions

Fixed Assignment

- User j assigned to base a_j .
- Assigned base fixed through iterations

$$p_j \geq I_j^{FA}(\boldsymbol{p}) = \frac{\gamma_j}{\mu_{a_j j}(\boldsymbol{p})}$$

γ_j : SIR requirement for user j

Interference Functions

Minimum Power Assignment

- User j assigned to base with maximum SIR_j
- Assigned base updated at each iteration

$$p_j \geq I_j^{MPA}(\boldsymbol{p}) = \min_k \frac{\gamma_j}{\mu_{kj}(\boldsymbol{p})}$$

γ_j : SIR requirement for user j

Interference Functions

Macro Diversity

- Received signals for user j at all base stations combined
  - Assume interfering signals appear independent,
  - Maximal ratio combining: $SIR_j = p_j \sum_k \mu_{kj}(\mathbf{p}) \geq \gamma_j$

$$p_j \geq I_j^{MD}(\mathbf{p}) = \frac{\gamma_j}{\sum_k \mu_{kj}(\mathbf{p})}$$

γ_j : SIR requirement for user j

Interference Functions

Limited Diversity

- Received signals for user j at the best k_j base stations combined
  - Define $K_j(\mathbf{p})$ s.t. $\forall k \in K_j(\mathbf{p}), k' \notin K_j(\mathbf{p}), \quad \mu_{kj}(\mathbf{p}) \geq \mu_{k'j}(\mathbf{p})$

  $K_j(\mathbf{p}) : d_j$ base stations with maximum SIR_j

$$p_j \geq I_j^{LD}(\mathbf{p}) = \frac{\gamma_j}{\sum_{k \in K_j(\mathbf{p})} \mu_{kj}(\mathbf{p})}$$

γ_j : SIR requirement for user j

Interference Functions

Multiple Connection Reception

- User j is required to maintain acceptable SIR at d_j distinct base stations.
  - $Notation: \langle n \rangle \min_k a_k$: nth smallest element of the set $\{a_k\}$

$$p_j \geq I_j^{MCR}(\mathbf{p}) = \langle d_j \rangle \min_k \frac{\gamma_j}{\mu_{kj}(\mathbf{p})}$$

γ_j : SIR requirement for user j

Interference Functions

Fixed Assignment	User j is assigned to base station a_j	$p_j \ge I_j^{FA}(\mathbf{p}) = \frac{\gamma_j}{\mu_{a_j j}(\mathbf{p})}$
Minimum Power Assignment	User j assigned to base that maximizes SIR	$p_j \ge I_j^{MPA}(\mathbf{p}) = \min_k \frac{\gamma_j}{\mu_{kj}(\mathbf{p})}$
Macro Diversity	All received signals of user j are combined	$p_j \ge I_j^{MD}(\mathbf{p}) = \frac{\gamma_j}{\sum_k \mu_{kj}(\mathbf{p})}$
Limited Diversity	Best k_j signals of user j combined	$p_j \ge I_j^{LD}(\mathbf{p}) = \frac{\gamma_j}{\sum_{k \in K_j(\mathbf{p})} \mu_{kj}(\mathbf{p})}$
Multiple Connection Reception	User j to connect d_j distinct bases	$p_j \ge I_j^{MCR}(\mathbf{p}) = \langle d_j \rangle \min_k \frac{\gamma_j}{\mu_{kj}(\mathbf{p})}$

γ_j : SIR requirement for user j

Standard Interference Function

Definition [Yates 95]:

Interference function $\mathbf{I}(\mathbf{p})$ is standard if

for all $\mathbf{p} \geq 0$ the following properties are satisfied:

Positivity: $\boldsymbol{I}(\boldsymbol{p}) > 0$

Monotonicity: If $p \geq p'$, then $\boldsymbol{I}(\boldsymbol{p}) \geq \boldsymbol{I}(\boldsymbol{p}')$

Scalability: For all $\alpha > 1$, $\alpha \boldsymbol{I}(\boldsymbol{p}) > \boldsymbol{I}(\alpha \boldsymbol{p}')$

$(\boldsymbol{p} > \boldsymbol{p}'$: strict inequality in all components.$)$

Standard Interference Function

Positivity: implied by nonzero background noise σ_k

Monotonicity: $\mu_{kj}(\boldsymbol{p}) \leq \mu_{kj}(\boldsymbol{p}') \quad (\boldsymbol{p} \geq \boldsymbol{p}')$

Scalability: $\mu_{kj}(\alpha\boldsymbol{p}) > \dfrac{\mu_{kj}(\boldsymbol{p}')}{\alpha} \quad (\alpha > 1)$

=> $\boldsymbol{I}^{FA}, \boldsymbol{I}^{MPA}, \boldsymbol{I}^{MD}, \boldsymbol{I}^{LD}$ and $\boldsymbol{I}^{MC}$ are standard!

Interference Functions

Fixed Assignment

- User j assigned to base a_j .
- Assigned base fixed through iterations

$$p_j \geq I_j^{FA}(\mathbf{p}) = \frac{\gamma_j}{\mu_{a_j j}(\mathbf{p})} = \gamma_j \frac{\sum_{i \neq j} h_{a_j i} p_i + \sigma_k}{h_{a_j j}}$$

γ_j : SIR requirement for user j

Synchronous Iterative Power Control [Yates 95]

Standard Power Control Algorithm

$$\boldsymbol{p}(t+1) = \boldsymbol{I}(\boldsymbol{p}(t))$$ ↗ Standard Interference Function

If $\mathbf{I}(\mathbf{p})$ is feasible (i.e., $\mathbf{p} \geq \mathbf{I}(\mathbf{p})$ has a feasible solution) then this iteration converges to the unique fixed point

$$\mathbf{p}^* = \mathbf{I}\left(\mathbf{p}^*\right)$$

which is also the minimum total transmit power.

Synchronous Iterative Power Control

Theorem 1: If the standard power control algorithm has a fixed point, then the fixed point is unique.

Proof: Suppose $\mathbf{p}$ and $\mathbf{p}'$ distinct fixed points

Positivity: $p_j > 0,\ p'_j > 0\ \forall j$

w.l.o.g., assume $\exists\ j$ s.t. $p_j < p'_j$.

$\Rightarrow \exists\ \alpha > 1$ s.t. $\alpha p \geq p'$ and $\alpha p_j = p'_j$ for some j

$$p'_j = I_j(\mathbf{p}') \leq I_j(\alpha \mathbf{p}) < \alpha I_j(\mathbf{p}) = \alpha p_j$$

Contradiction

Monotonicity (for $\leq$)   Scalability (for $<$)

□

Synchronous Iterative Power Control

Lemma 1: If $\boldsymbol{p}$ is a feasible power vector, then $\boldsymbol{I}^n(\boldsymbol{p})$, the sequence of iterations, is a monotone decreasing sequence of feasible power vectors converging to unique fixed point $\boldsymbol{p}^*$

Proof: Let $\boldsymbol{p}(0)=\boldsymbol{p}$, and $\boldsymbol{p}(n)=\boldsymbol{I}^n(\boldsymbol{p})$.

$\boldsymbol{p}$ feasible => $\boldsymbol{p}(0) \geq \boldsymbol{I}(\boldsymbol{p}(0)) = \boldsymbol{p}(1)$. Suppose $\boldsymbol{p}(n-1) \geq \boldsymbol{p}(n)$,

Monotonicity: $\underbrace{\boldsymbol{I}(\boldsymbol{p}(n-1))}_{\boldsymbol{p}(n)} \geq \underbrace{\boldsymbol{I}(\boldsymbol{p}(n))}_{\boldsymbol{p}(n+1)},$

By induction, $\boldsymbol{p}(n)$ is a decreasing sequence.

Since $\boldsymbol{p}(n) \geq 0$, it must converge to unique $\boldsymbol{p}^*$ in Thm 1

□

Synchronous Iterative Power Control

Lemma 2: If $\mathbf{I}(\mathbf{p})$ is feasible, then starting from $\mathbf{z}$, the all zero vector, the standard power control algorithm produces a monotone increasing sequence $\mathbf{I}^n(\mathbf{z})$ that converges to $\mathbf{p}^*$.

Proof: Let $\mathbf{z}(n) = \mathbf{I}^n(\mathbf{z})$. Observe $\mathbf{z} = \mathbf{z}(0) < \mathbf{p}^*$ and $\mathbf{z}(1) = \mathbf{I}(\mathbf{z}) \geq \mathbf{z}$.

Suppose $\mathbf{z}(n-1) \leq \mathbf{z}(n) \leq \mathbf{p}^*$. Then

Monotonicity: $$\mathbf{p}^* = \mathbf{I}(\mathbf{p}^*) \geq \underbrace{\mathbf{I}(\mathbf{z}(n))}_{\mathbf{z}(n+1)} \geq \underbrace{\mathbf{I}(\mathbf{z}(n-1))}_{\mathbf{z}(n)}$$

$$\Rightarrow \mathbf{p}^* \geq \mathbf{z}(n+1) \geq \mathbf{z}(n),$$

By induction, $\mathbf{z}(n)$ is an increasing sequence $\leq \mathbf{p}^*$.

Since $\mathbf{z}(n)$ upper bounded, it must converge to $\mathbf{p}^*$ □

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Synchronous Iterative Power Control

Theorem 2: If $\boldsymbol{I}(\mathbf{p})$ is feasible, then for any initial vector $\mathbf{p}$, the standard power control algorithm converges to a unique fixed point $\mathbf{p}^*$.

Proof: Since $p_j^* > 0\ \forall j$, for any $\mathbf{p}$ one can find $\alpha \geq 1$ s.t. $\alpha \mathbf{p}^* \geq \mathbf{p}$

Scalability: $\alpha \mathbf{p}^*$ must be feasible (since $\mathbf{p}^*$ feasible)

Monotonicity: $\mathbf{z} \leq \mathbf{p} \leq \alpha \mathbf{p}^* \quad \Rightarrow \quad \boldsymbol{I}^n(\mathbf{z}) \leq \boldsymbol{I}^n(\mathbf{p}) \leq \boldsymbol{I}^n(\alpha \mathbf{p}^*)$

$$\lim_{n\to\infty} \boldsymbol{I}^n(\alpha \mathbf{p}^*) = \mathbf{p}^* \quad \text{(Lemma 1)}$$

$$\lim_{n\to\infty} \boldsymbol{I}^n(\mathbf{z}) = \mathbf{p}^* \quad \text{(Lemma 2)}$$

$$\lim_{n\to\infty} \boldsymbol{I}^n(\mathbf{p}) = \mathbf{p}^* \text{ for any } \mathbf{p}$$

□

Synchronous Iterative Power Control

Summary: For any feasible interference function satisfying positivity, monotonicity and scalability, the standard iterative algorithm

$$\boldsymbol{p}(t+1) = \boldsymbol{I}(\boldsymbol{p}(t))$$

converges to the unique fixed point $\boldsymbol{p}^* = \boldsymbol{I}(\boldsymbol{p}^*)$

which corresponds to minimum total transmitted power

Asynchronous Power Control

Totally asynchronous algorithm model

"Parallel and Distributed Computation"

Bertsekas and Tsiksitlis, Prentice Hall, 1989

Allows users to:

- Perform power adjustments faster
- Execute more iterations than others
- Use outdated information on interference

Asynchronous Power Control

Totally asynchronous algorithm model

$p_j(t)$: transmitted power of user j at time t

$$\mathbf{p}(t) = \left(p_1(t), p_2(t), \ldots, p_N(t)\right)$$

At time t, user j adjusts its transmission power using

$$\mathbf{p}(\tau^j(t)) = \left(p_1(\tau_1^j(t)), p_2(\tau_2^j(t)), \ldots, p_N(\tau_N^j(t))\right)$$

$\tau_i^j(t)$: most recent time for which $p_i(t)$ is known to user j

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Asynchronous Power Control

Totally Asynchronous

Standard Power Control Algorithm

$$p_j(t+1) = \begin{cases} I_j(\mathbf{p}(\tau^j(t))) & t \in T^j \\ p_j(t) & otherwise \end{cases}$$

T^j : set of times at which a component $p_j(t)$ of $\mathbf{p}(t)$ is updated.

Asynchronous Power Control

Asynchronous Convergence Theorem

If there is a sequence of nonempty sets $\{X(n)\}$

with $X(n+1) \subset X(n)$ for all n satisfying :

1)Synchronous Convergence Condition: $\forall n, x \in X(n), f(x) \in X(n+1)$

If $\{y^n\}$ is a sequence s.t. $y^n \in X(n)\ \forall n,$

then every limit point of $\{y^n\}$ is a fixed point of f.

2)Box Condition: For every n, $\exists$ sets $X_i(n) \in X_i$ s.t.

$X(n) = X_1(n) \times X_2(n) \times ... \times X_N(n).$

and the initial estimate $x(0) \in X(0)$, then every limit point of $\{x(t)\}$ is a fixed point of f.

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Asynchronous Power Control

Theorem 4: If $\mathbf{I}(\mathbf{p})$ is feasible, then for an initial vector $\mathbf{p}$, the asynchronous standard power control algorithm converges to $\mathbf{p}^*$.

Proof: Since $\boldsymbol{I}(\boldsymbol{p})$ is feasible, a fixed point $\boldsymbol{p}^*$ exists.

Let $\boldsymbol{X}(n) = \{\boldsymbol{p} \mid \boldsymbol{I}^n(z) \le \boldsymbol{p} \le \boldsymbol{I}^n(\alpha\boldsymbol{p}^*)\}$ for some $\alpha \ge 1$ s.t. $\alpha\boldsymbol{p}^* > \boldsymbol{p}$

$\boldsymbol{X}(n)$ satisfies *Box Condition* with $\boldsymbol{X}_i = \{p_i | I_i^n(z) \le p_i \le I_i^n(\alpha p_i^*)\}$

Lemmas 1&2 imply $\boldsymbol{X}(n+1) \subset \boldsymbol{X}(n)$ and $\lim_{n\to\infty} \boldsymbol{I}^n(\alpha\boldsymbol{p}^*) = \lim_{n\to\infty} \boldsymbol{I}^n(\boldsymbol{z}) = \boldsymbol{p}^*$

$\Rightarrow \boldsymbol{X}(n)$ satisfies *Synchronous Convergence Condition*

□

Extensions to Framework

Interference Alternatives (e.g. for network MIMO)

Suppose user j is given a choice between $I_j(\mathbf{p})$ and $I'_j(\mathbf{p})$

(e.g. communicate with base k and k' at different SIRs)

User may choose to satisfy *either one* or *both* by satisfying:

$$I_j^{\min}(\mathbf{p}) = \min\left\{I_j(\mathbf{p}), I'_j(\mathbf{p})\right\} \qquad I_j^{\max}(\mathbf{p}) = \max\left\{I_j(\mathbf{p}), I'_j(\mathbf{p})\right\}$$

It can easily be verified that

$\mathbf{I}(\mathbf{p})$ and $\mathbf{I}'(\mathbf{p})$ standard $\Rightarrow$ $\mathbf{I}^{\min}(\mathbf{p})$ and $\mathbf{I}^{\max}(\mathbf{p})$ also standard!

Standard Power Control Algorithms converge to $\mathbf{p}^*$

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Extensions to Framework

Maximum and Minimum Power Constraints

Suppose user j has a maximum or minimum power $q_j > 0$

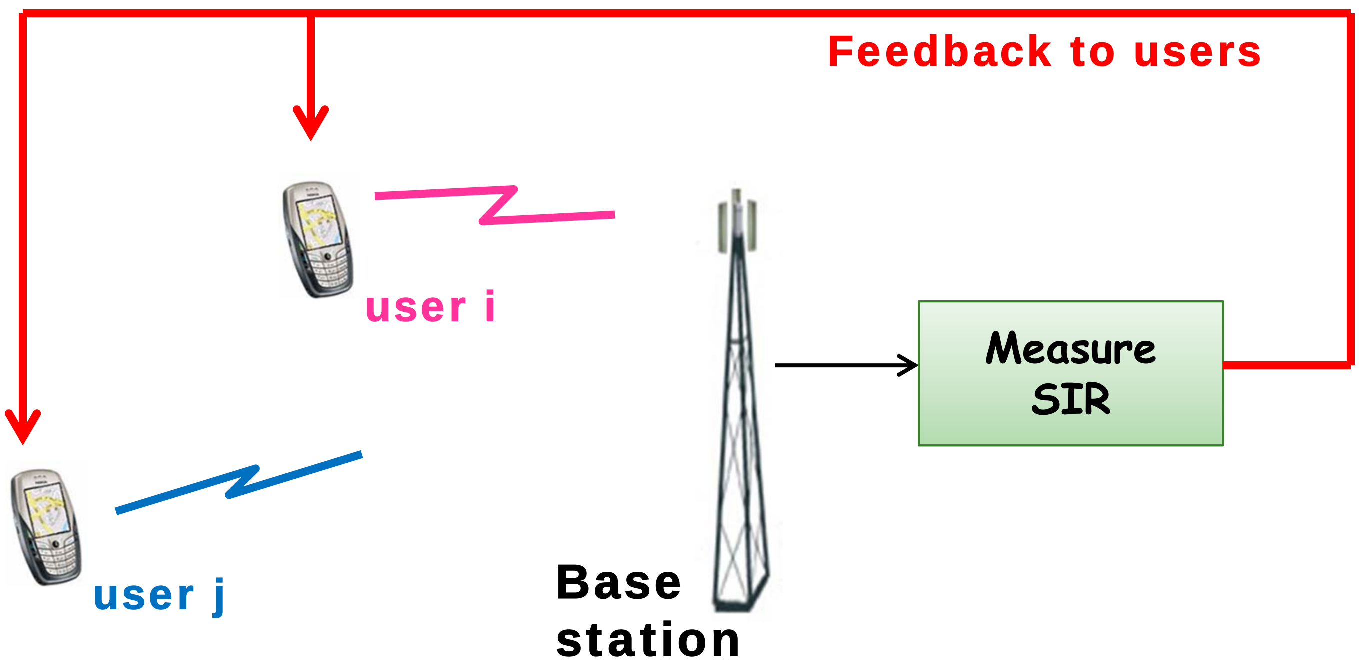
Define $\boldsymbol{I}^{(q)}(\boldsymbol{p}) = \boldsymbol{q}$. This interference function is standard!

Let $\hat{I}_j^{(q)}(\boldsymbol{p}) = \min\{I_j^{(q)}(\boldsymbol{p}), I_j(\boldsymbol{p})\}$ (Minimum Power Cnst.)

$\tilde{I}_j^{(q)}(\boldsymbol{p}) = \max\{I_j^{(q)}(\boldsymbol{p}), I_j(\boldsymbol{p})\}$ (Maximum Power Cnst.)

$\hat{\boldsymbol{I}}^{(q)}(\boldsymbol{p})$ and $\tilde{\boldsymbol{I}}^{(q)}(\boldsymbol{p})$ are standard, and satisfy power constraints.

Conventional Power Control



$$p_j(t+1) = I_j^{FA}(\mathbf{p}(t)) = \frac{\gamma_j}{SIR_j(t)} p_j(t)$$

Temporal and Spatial Filtering

- Receivers can be designed to be "better" (in the sense of handling interference) and jointly optimized with transmit powers for improved EE.
- This necessitates looking into signal space dimensions of transmitted signals
- Assume we have temporal (CDMA) and spatial dimensions (multiple antennas at the base)

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Temporal-Spatial Filtering

System Model:

- CDMA System with N users:
  - processing gain G
  - K array elements
- Temporal signature sequence of user j: $s_j(t)$
- Spatial signature sequence of user j: $a_j(t)$

Linear Multiuser Detection (Temporal Filtering)

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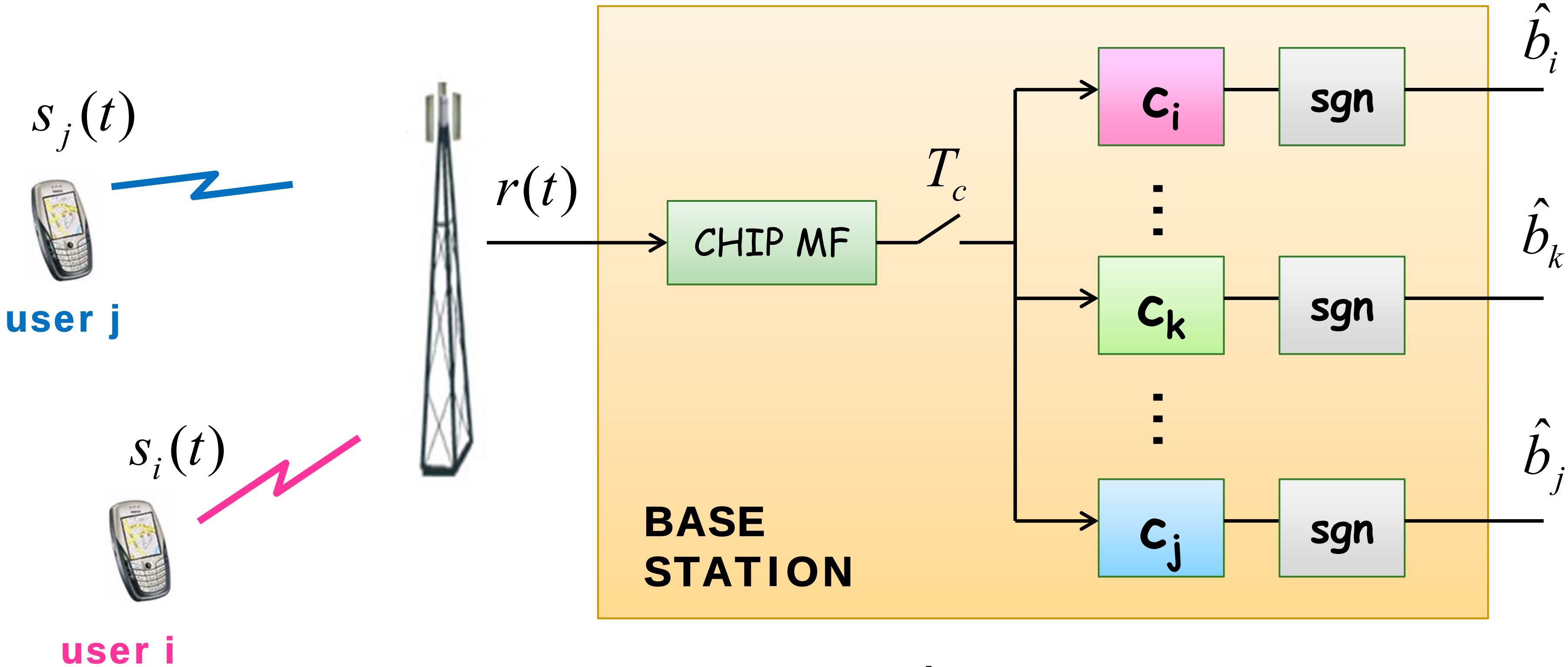

$$\hat{b}_i = \mathrm{sgn}(\boldsymbol{c}_i^T \boldsymbol{r})$$

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Linear Multiuser Detection (Temporal Filtering)

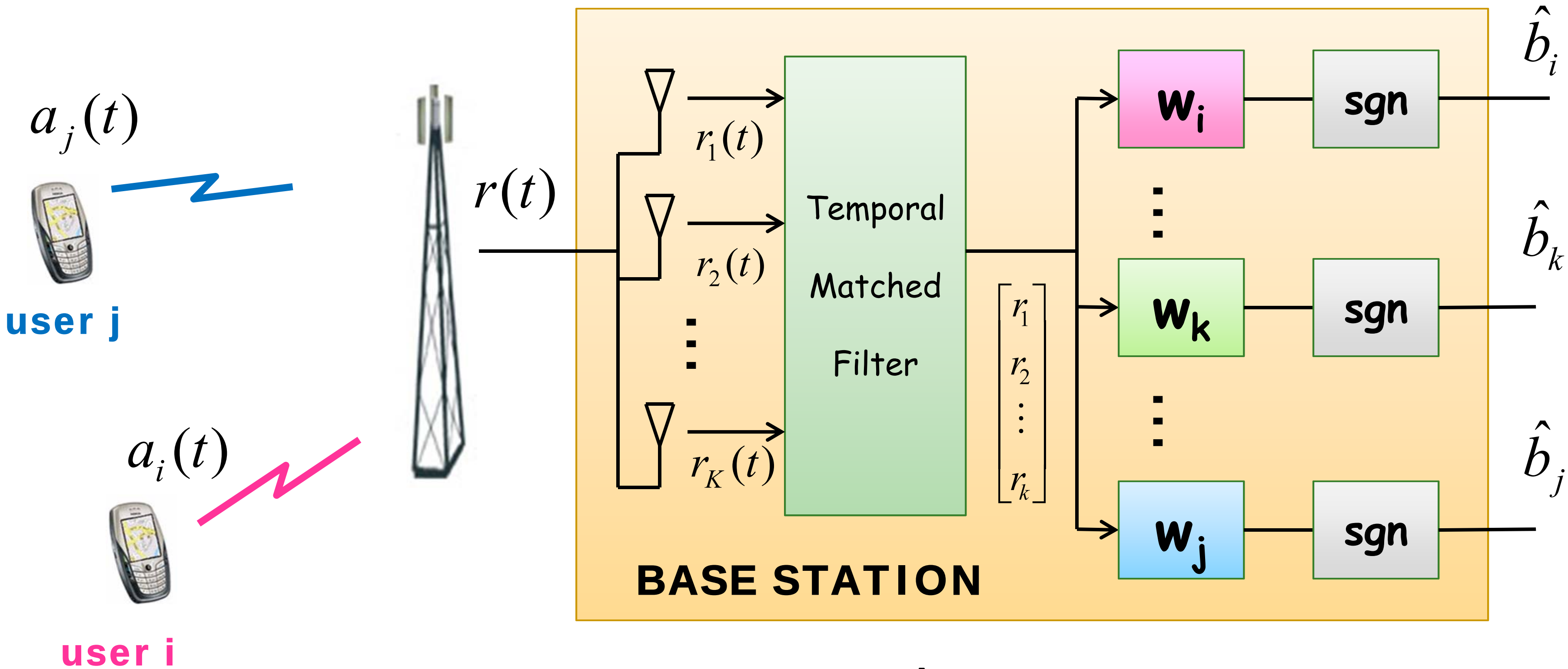
- User j has temporal signature sequence $s_j(t)$
- Received signal is chip-match filtered and sampled to get:

$$\boldsymbol{r} = \sum_{j=1}^{N} \sqrt{p_j h_j} b_j \boldsymbol{s}_j + \boldsymbol{n}$$

- MMSE combiner gives estimate of bit as

$$\hat{b}_i = \mathrm{sgn}(\boldsymbol{c}_i^T \boldsymbol{r})$$

Beamforming (Spatial Filtering)



$$\hat{b}_i = \mathrm{sgn}(\boldsymbol{w}_i^T \boldsymbol{r})$$

Beamforming (Spatial Filtering)

- User j has spatial signature sequence $a_j(t)$
- Received signal is temporal match filtered to get:

$$\boldsymbol{r} = \sum_{j=1}^{N} \sqrt{p_j h_j} b_j \boldsymbol{a}_j + \boldsymbol{n}$$

- MMSE combiner gives estimate of bit as

$$\hat{b}_i = \text{sgn}(\boldsymbol{w}_i^T \boldsymbol{r})$$

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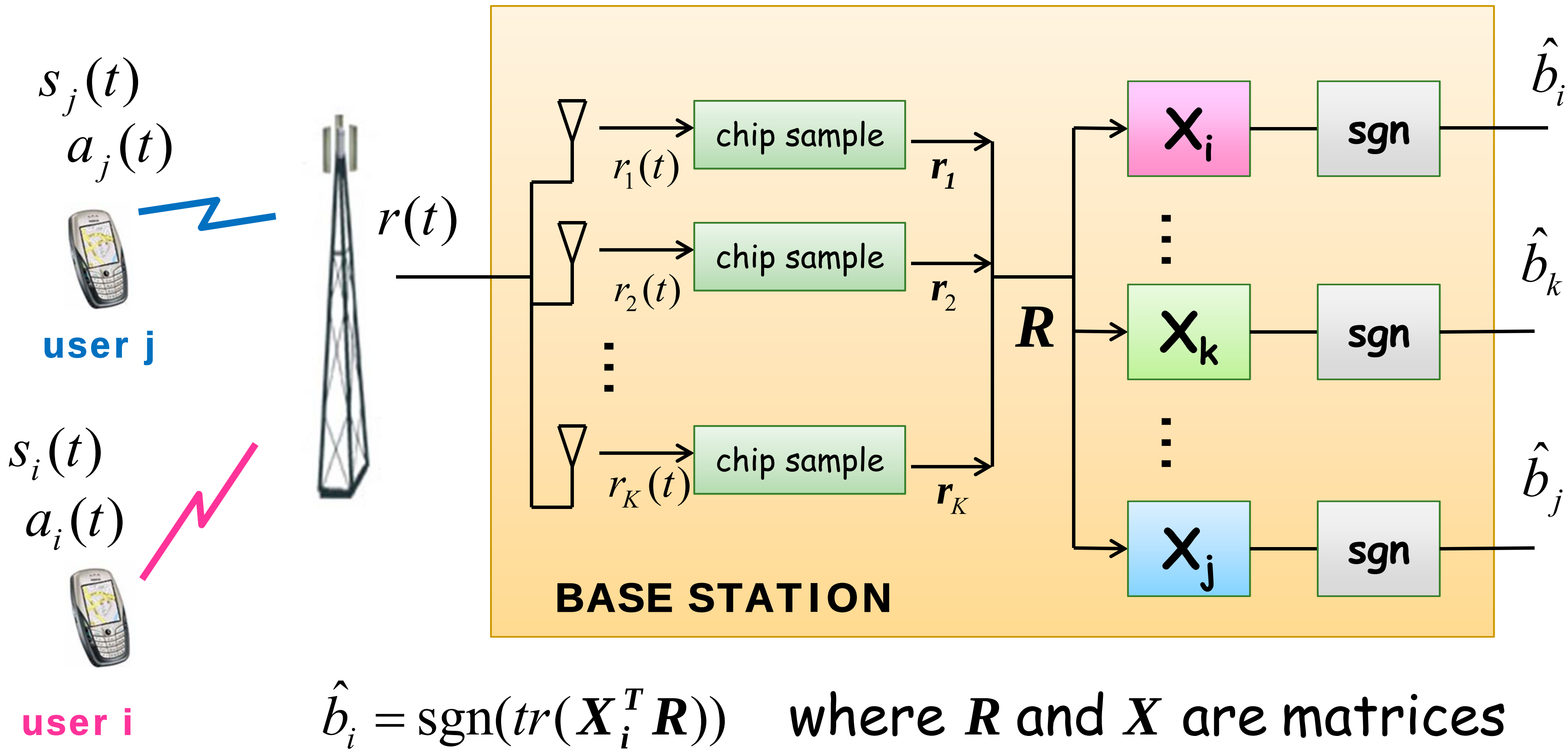
Temporal and Spatial Filtering



$\hat{b}_i = \text{sgn}(tr(\boldsymbol{X}_i^T \boldsymbol{R}))$ where $\boldsymbol{R}$ and $\boldsymbol{X}$ are matrices

Temporal and Spatial Filtering

- User j has both temporal signature sequence $s_j(t)$ and spatial signature sequence $a_j(t)$
- Received signal at the output of each array element is chip-matched filtered and sampled to get:

$$\boldsymbol{R} = \sum_{j=1}^{N} \sqrt{p_j h_j} b_j \mathbf{s}_j \boldsymbol{a}_j^T + \boldsymbol{N}$$

$(\boldsymbol{R} : G \times K$ matrix$)$

- How to choose the linear matrix filter?

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Temporal and Spatial Filtering [Yener et.al. 01]

Linear filter: $y_i = \sum_{j=1}^{G} \sum_{l=1}^{K} [\boldsymbol{X}_i]_{jl}^{*} [\boldsymbol{R}]_{jl} = tr\left(\boldsymbol{X}_i^H \boldsymbol{R}\right)$

- Single user: $\boldsymbol{X}_i^{MF-MF} = \boldsymbol{s}_i \boldsymbol{a}_i^T$
- Single user – multiuser: $\boldsymbol{X}_i^{MMSE-MF} = \boldsymbol{c}_i \boldsymbol{a}_i^T$

  $\boldsymbol{X}_i^{MF-MMSE} = \boldsymbol{s}_i \boldsymbol{w}_i^T$
- Cascaded filter structures

Optimum Temporal-Spatial Filter (OTSF)

- Find $\boldsymbol{X}_i$ that yields the minimum MSE between y_i and b_i.

$$\boldsymbol{X}_i^{O-MMSE} = \arg\min_{\boldsymbol{X}} E[(tr(\boldsymbol{X}_i^H \boldsymbol{R}) - b_i)^2]$$

- Resulting joint optimum filter has a closed form
- Requires KGxKG matrix inversion

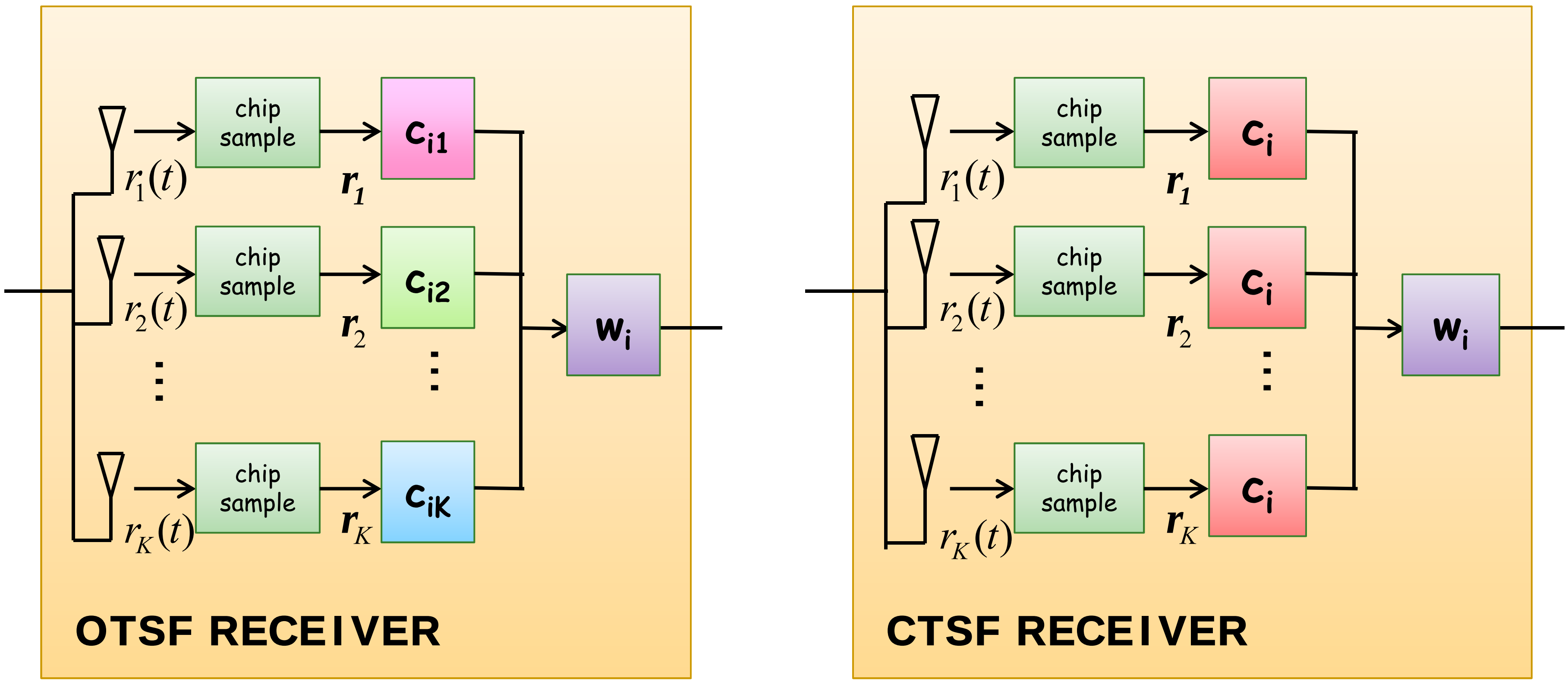
Constrained Temporal-Spatial Filter (CTSF)

- Less complex filters with near-optimum performance
- **Approach:** Separable filters: $\tilde{\boldsymbol{X}}_i = \boldsymbol{c}_i \boldsymbol{w}_i^T$
- Decision statistic for user i:

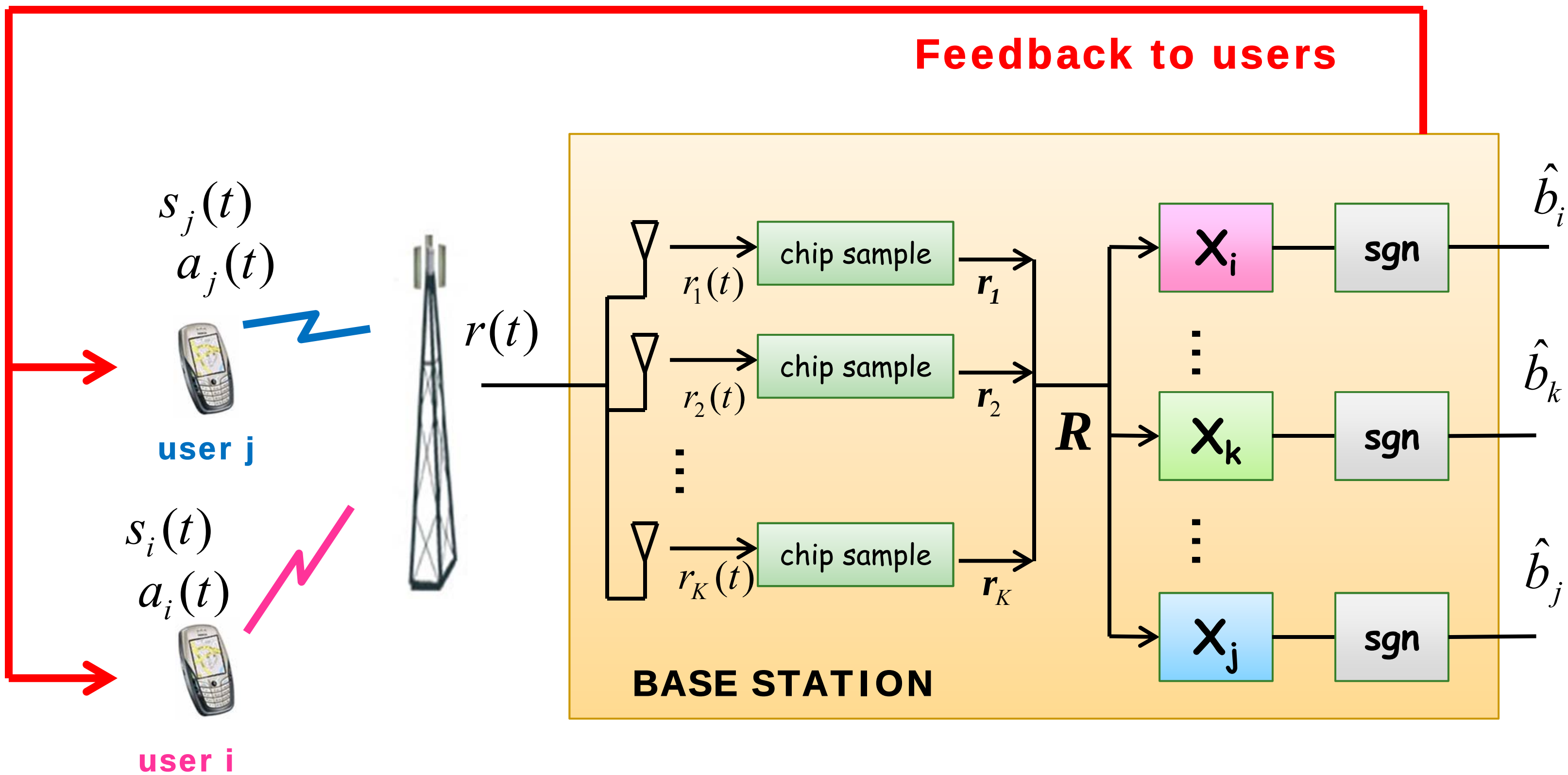
$$y_i = tr(\boldsymbol{w}_i \boldsymbol{c}_i^T \boldsymbol{R}) = \boldsymbol{c}_i^T \boldsymbol{R} \boldsymbol{w}_i$$

- Iterative algorithms to optimize one filter at a time

OTSF vs CTSF Receiver
(for user i)



Power Control + Multiuser Detection + Beamforming



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Power Control and Temporal-Spatial Filtering

Problem: Find optimal p_i and $X_i, \forall i,$ such that

- The total transmitter power is minimized
- Each user i satisfies $SIR_i \geq \gamma_i^*$

- Power+filter optimization for both OTSF and OCTSF:

$$\min_{\{p_i, \boldsymbol{X}_i\}} \sum_{i=1}^{N} p_i$$

$$s.t. \quad SIR_i \geq \gamma_i^* \quad (SIR_i \text{ is a function of } \boldsymbol{X}_i \text{ and } \mathbf{p})$$

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Power Control and Temporal-Spatial Filtering

Solution: $\boldsymbol{X}_i$ optimization can be moved to SIR constraint :

$$\min_{\{p_i\}} \sum_{i=1}^{N} p_i$$
$$s.t. \quad p_i \ge \min_{\boldsymbol{X}_i} g_i(SIR_i) \quad i = 1, \dots, N$$

- Minimizing $g_i(.)$ over $\boldsymbol{X}_i \equiv$ maximizing SIR_i for fixed p_i
- MMSE temporal-spatial filters, OTSF and OCTSF maximize the output SIR of desired user.

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Power Control and Temporal-Spatial Filtering

Solution: X_i optimization can be moved to SIR constraint :

$$\min_{\{p_i\}} \sum_{i=1}^{N} p_i$$

$$s.t. \quad p_i \geq \min_{\boldsymbol{X}_i} g_i(SIR_i) \quad i = 1, \ldots, N$$

- This implies that X_i that maximizes $g_i(.)$ is the
  - OTSF if joint domain filters are to be employed
  - OCTSF if separable filters are to be employed

Iterative Power Control Algorithm

- Design an iterative power and temporal-spatial filter updating algorithm that converges to the optimum powers and corresponding filters.

For each user i, at step n:

1) Given $\mathbf{p}(n)$, find the corresponding best filter (OTSF or OCTSF) $\boldsymbol{X}_i(n+1)$. The SIR of user i with this new filter is $SIR_i(n+1)$.

2) Update the transmit power of the user as

$$p_i(n+1) = \frac{\gamma_i^*}{SIR_i(n+1)} p_i(n)$$

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Iterative Power Control Algorithm

$$SIR_i = \frac{p_i h_{ii} \left| tr(\boldsymbol{X}_i^H \mathbf{s}_i \boldsymbol{a}_{ii}^T) \right|^2}{\sum_{j \neq i} p_j h_{ij} \left| tr(\boldsymbol{X}_i^H \mathbf{s}_j \boldsymbol{a}_{ij}^T) \right|^2 + \sigma^2 tr(\boldsymbol{X}_i^H \boldsymbol{X}_i)} \geq \gamma_i^*$$

$$\boldsymbol{p} \geq \boldsymbol{I}(\boldsymbol{p})$$

$$I_i(\boldsymbol{p}) = \frac{\gamma_i^*}{SIR_i} p_i = \frac{\gamma_i^*}{h_{ii}} \min_{\boldsymbol{X}_i \in \boldsymbol{S}} \frac{\sum_{j \neq i} p_j h_{ij} \left| tr(\boldsymbol{X}_i^H \mathbf{s}_j \boldsymbol{a}_{ij}^T) \right|^2 + \sigma^2 tr(\boldsymbol{X}_i^H \boldsymbol{X}_i)}{\left| tr(\boldsymbol{X}_i^H \mathbf{s}_i \boldsymbol{a}_{ii}^T) \right|^2}$$

Thm [Yener01]: $\boldsymbol{I}(\boldsymbol{p})$ is a standard interference function

Iterative Power Control Algorithm

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Proof: Define

$$J_i(\mathbf{p},\mathbf{X}_i)=\frac{\gamma_i^*}{h_{ii}}\frac{\sum_{j\neq i}p_j h_{ij}\left|tr(\mathbf{X}_i^H\mathbf{s}_j\mathbf{a}_{ij}^T)\right|^2+\sigma^2 tr(\mathbf{X}_i^H\mathbf{X}_i)}{\left|tr(\mathbf{X}_i^H\mathbf{s}_i\mathbf{a}_{ii}^T)\right|^2}$$

so that $I_i(\mathbf{p})=\min_{\mathbf{X}_i\in\mathbf{S}}J_i(\mathbf{p},\mathbf{X}_i)$

$$\mathbf{S}=\begin{cases}C^{G\times K} & \text{OTSF}\\ \mathcal{L} & \text{OCTSF}\end{cases}$$

Positivity: $J_i(\mathbf{p},\mathbf{X}_i)>0$ for any fixed $\mathbf{X}_i$

Therefore $I_i(\mathbf{p})=\min_{\mathbf{X}_i\in\mathbf{S}}J_i(\mathbf{p},\mathbf{X}_i)>0$

Iterative Power Control Algorithm

Monotonicity:

$$J_i(\mathbf{p},\mathbf{X}_i)=\frac{\gamma_i^*}{h_{ii}}\frac{\sum_{j\neq i}p_j h_{ij}\left|tr(\mathbf{X}_i^H\mathbf{s}_j\mathbf{a}_{ij}^T)\right|^2+\sigma^2 tr(\mathbf{X}_i^H\mathbf{X}_i)}{\left|tr(\mathbf{X}_i^H\mathbf{s}_i\mathbf{a}_{ii}^T)\right|^2}$$

For fixed $\mathbf{X}_i,\;\; \mathbf{p}\ge\mathbf{p}'\Rightarrow J_i(\mathbf{p},\mathbf{X}_i)\ge J_i(\mathbf{p},\mathbf{X}_i)$

$$\begin{aligned}I_i(\mathbf{p})&=\min_{\mathbf{X}_i\in\mathbf{S}}J_i(\mathbf{p},\mathbf{X}_i)\\&=J_i(\mathbf{p},\mathbf{X}_i^*)\\&\ge J_i(\mathbf{p}',\mathbf{X}_i^*)\\&\ge\min_{\mathbf{X}_i\in\mathbf{S}}J_i(\mathbf{p}',\mathbf{X}_i)=I_i(\mathbf{p}')\end{aligned}$$

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Scalability:

$$J_i(\mathbf{p}, \boldsymbol{X}_i) = \frac{\gamma_i^*}{h_{ii}} \frac{\sum_{j \neq i} p_j h_{ij} \left| tr(\boldsymbol{X}_i^H \mathbf{s}_j \boldsymbol{a}_{ij}^T) \right|^2 + \sigma^2 tr(\boldsymbol{X}_i^H \boldsymbol{X}_i)}{\left| tr(\boldsymbol{X}_i^H \mathbf{s}_i \boldsymbol{a}_{ii}^T) \right|^2}$$

For fixed $\boldsymbol{X}_i$ and $\alpha > 1$, $\alpha J_i(\mathbf{p}, \boldsymbol{X}_i) > J_i(\alpha \mathbf{p}, \boldsymbol{X}_i)$

$$\begin{aligned} \alpha I_i(\mathbf{p}) &= \min_{\boldsymbol{X}_i \in \boldsymbol{S}} \alpha J_i(\mathbf{p}, \boldsymbol{X}_i) \\ &= \alpha J_i(\mathbf{p}, \boldsymbol{X}_i^*) \\ &> J_i(\alpha \mathbf{p}', \boldsymbol{X}_i^*) \\ &\geq \min_{\boldsymbol{X}_i \in \boldsymbol{S}} J_i(\alpha \mathbf{p}', \boldsymbol{X}_i) = I_i(\alpha \mathbf{p}') \end{aligned}$$

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Iterative Power Control Algorithm

Summary

$\boldsymbol{I}(\boldsymbol{p})$ is standard,

$$p_i(t+1) = I_i(\boldsymbol{p}(t)) = \frac{\gamma_i^*}{h_{ii}} \min_{\boldsymbol{X}_i \in \boldsymbol{S}} \frac{\sum_{j \neq i} p_j h_{ij} \left| tr(\boldsymbol{X}_i^H \boldsymbol{s}_j \boldsymbol{a}_{ij}^T) \right|^2 + \sigma^2 tr(\boldsymbol{X}_i^H \boldsymbol{X}_i)}{\left| tr(\boldsymbol{X}_i^H \boldsymbol{s}_i \boldsymbol{a}_{ii}^T) \right|^2}$$

converges to unique power-minimizing fixed point $\boldsymbol{p}^* = \boldsymbol{I}(\boldsymbol{p}^*)$

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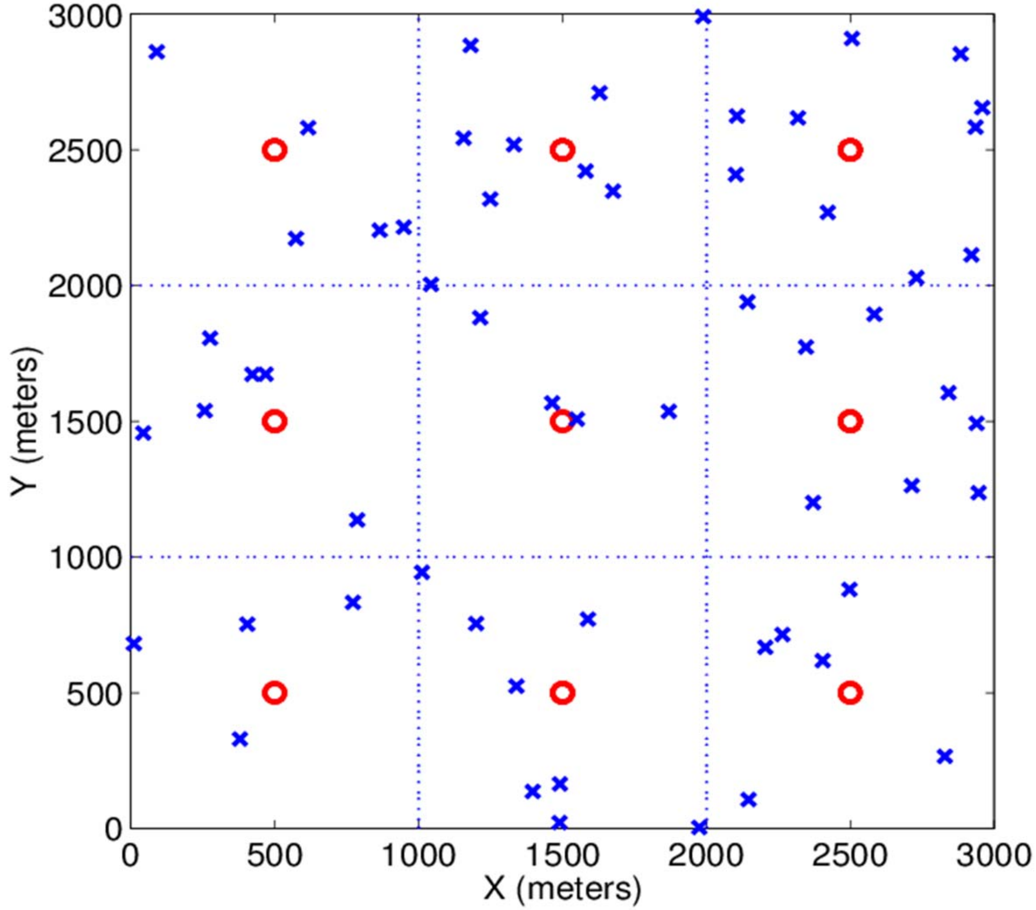
Numerical Results

- 9-cell CDMA system, $G = 10, \ \gamma^* = 5 \ (7dB)$
- Random temporal signatures, equispaced $(\lambda/2)$ linear omni directional array
- Results are generated to compare:
  - Contentional Power Control (C-PC)
  - Power control and MMSE beamforming (BF-PC)
  - Power control and MMSE multiuser detection (MMSE-PC)
  - Power control with OCTSF(CTSF-PC). L=5 iterations of CTSF
  - Power control with one step CTSF (c-w-PC). L=1
  - Power control with OTSF (OTSF-PC)

Numerical Results

User Distribution Example for N=60



Numerical Results

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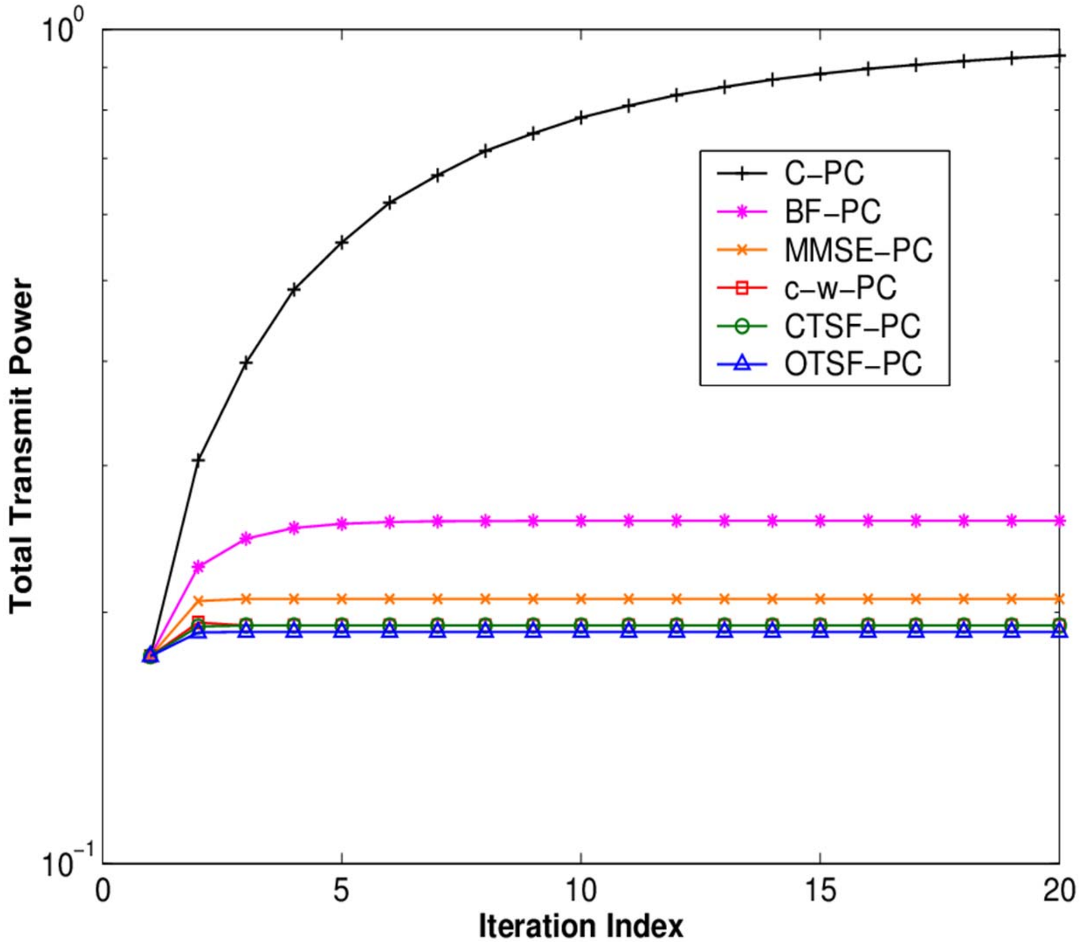
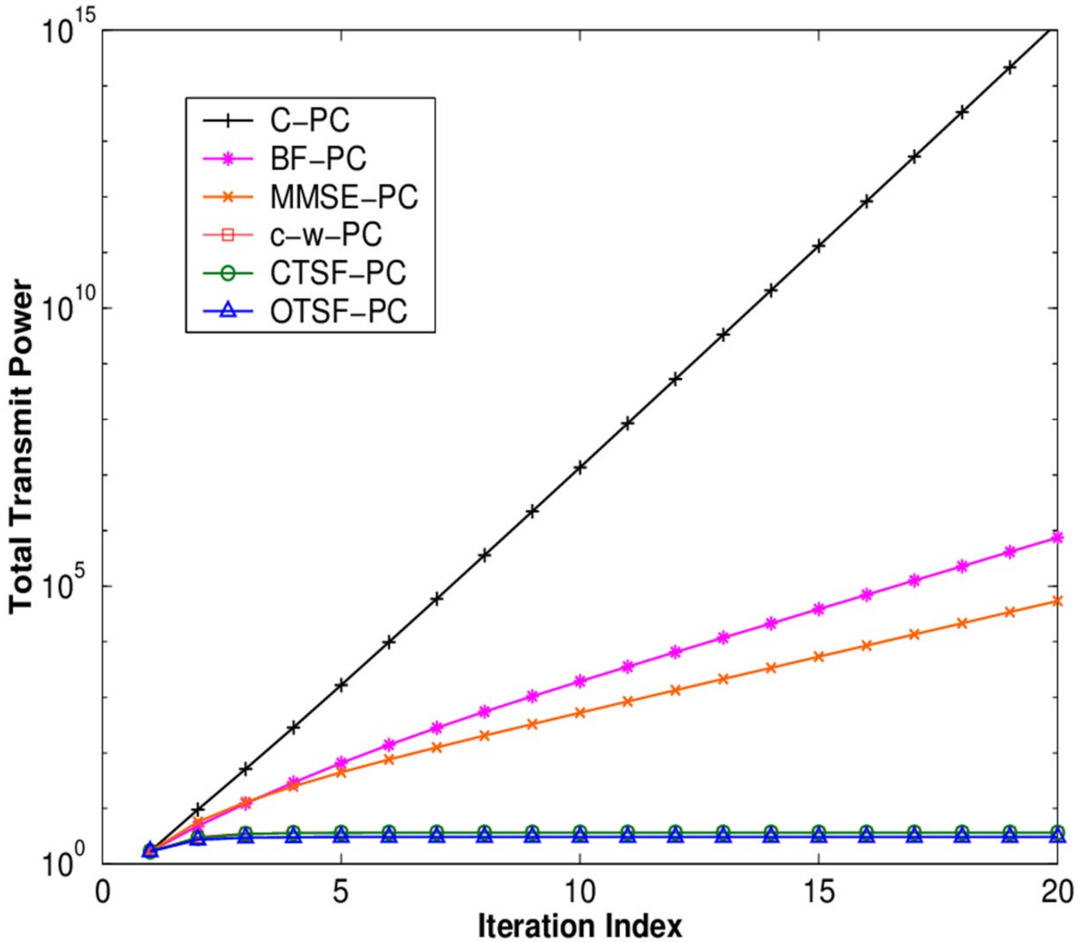
Total transmitter power $\left(N=12,\ G=10,\ K=2\right)$



- Joint spatial temporal algorithms offer total transmit power savings
- Compared to C-PC, the savings are as high as 7.2dB.

Simulation Results

Total transmitter power $\left(N = 60,\ G = 10,\ K = 4\right)$



- Joint spatial temporal algorithms convert an otherwise infeasible system into a feasible one!

Conclusions

- Energy efficiency for classical single charge networks is tantamount to power efficiency in transmission.
- Effective management of interference is possible by receiver design; jointly optimizing receivers with powers provides the most energy efficient option.

Conclusions/Outlook

- For classical networks energy efficiency is not necessarily new, there are however topics less mature then others:
- **Multi-tier** network design: Can femtocells help us be more green?
- Green base stations? Need to care about
  - downlink transmit energy (some existing work)
  - processing energy (very little work)

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