Space Time Coding for DS-CDMA

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EECS 555: Digital Communication Theory

April 29, 2004

Outline

References

B. Hochwald, T. Marzetta and C. Papadias
A Transmitter Diversity Scheme for Wideband CDMA Systems Based on Space-Time Spreading
IEEE JSAC, Vol. 19, No. 1, January 2001

A. J. Viterbi
CDMA : Principles of Spread Spectrum Communication
Prentice Hall PTR, 17 April, 1995

Proposed TDCO #662/98 TO ETSI SMG2 UMTS standards, Dec. 1998
Space Time Block Coded Transmit Antenna Diversity Scheme for WCDMA

V. Tarokh, H. Jafarkhani and A.R. Calderbank,
Space-time block codes from orthogonal design
IEEE Trans. Inform. Theory, Vol. 45, July 99

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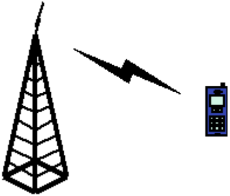
1. Multiple Antenna Downlink Schemes
2. Space Time Spreading
3. Main Results of Hochwald et. al. (2001)
   - Imperfect Channel Estimation
   - Single User — Multipath Components
4. Multiuser Interference
   - Effect of Number of users
   - Bounds as Compared to Actual Performance
5. Conclusion

Single Antenna System

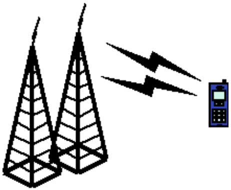


(Antenna 1)

$$\boldsymbol{s}_1 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} b(k)\boldsymbol{c}(k)$$

$$\boldsymbol{c}^\dagger(k)\boldsymbol{r} = N\sqrt{\frac{E_c(k)}{2}} h_1 b(k) + \boldsymbol{c}^\dagger(k)\boldsymbol{n}$$

Two Antenna System



(Antenna 2)

$$\boldsymbol{s}_2 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} b(k)\boldsymbol{c}(k)$$

$$\boldsymbol{r} = h_1\boldsymbol{s}_1 + h_2\boldsymbol{s}_2 + \boldsymbol{n}$$

$$\boldsymbol{c}^\dagger(k)\boldsymbol{r} = N\sqrt{\frac{E_c(k)}{2}} (h_1 + h_2) b(k) + \boldsymbol{c}^\dagger(k)\boldsymbol{n}$$

Two Distinct Spreading Codes for Each User

(Antenna 1) $$\boldsymbol{s}_1 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} b(k) \boldsymbol{c}_1(k)$$

(Antenna 2) $$\boldsymbol{s}_2 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} b(k) \boldsymbol{c}_2(k)$$

(Received Signal) $$\boldsymbol{r} = h_1 \boldsymbol{s}_1 + h_2 \boldsymbol{s}_2 + \boldsymbol{n}$$

$$y = \left(h_1^* \boldsymbol{c}_1^\dagger(k) + h_2^* \boldsymbol{c}_2^\dagger(k)\right) \boldsymbol{r} = N \sqrt{\frac{E_c(k)}{2}} \overbrace{\left(|h_1|^2 + |h_2|^2\right)}^{\text{Diversity} = 2} b(k) + \eta$$

$$y \underset{b(k)=-1}{\overset{b(k)=+1}{\gtrless}} 0$$

Advantages

- Rate = 1 code
- Optimal two-fold diversity gain over single antenna case
- Linear Complexity Receiver

Disadvantages

- Two code sequences per user
  Effective number of users halved

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Achieve two-fold diversity with rate = 1 code without reducing the total number of users in the system

Solution

Space-Time Spreading (STS)

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Space Time Spreading

(Antenna 1) $$\boldsymbol{s}_1 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} \left(b_1(k)\boldsymbol{c}_1(k) + b_2(k)\boldsymbol{c}_2(k)\right)$$

(Antenna 2) $$\boldsymbol{s}_2 = \sum_{k=1}^{K_u} \sqrt{\frac{E_c(k)}{2}} \left(b_2(k)\boldsymbol{c}_1(k) - b_1(k)\boldsymbol{c}_2(k)\right)$$

(Rcvd Signal) $$\boldsymbol{r} = h_1\boldsymbol{s}_1 + h_2\boldsymbol{s}_2 + \boldsymbol{n}$$

$$y_1 = \mathrm{Re}\left\{ \left(h_1^*\boldsymbol{c}_1^\dagger(k) - h_2^*\boldsymbol{c}_2^\dagger(k)\right)\boldsymbol{r} \right\}$$

$$y_2 = \mathrm{Re}\left\{ \left(h_2^*\boldsymbol{c}_1^\dagger(k) + h_1^*\boldsymbol{c}_2^\dagger(k)\right)\boldsymbol{r} \right\}$$

$$\Rightarrow \quad y_i = 2N\sqrt{\frac{E_c(k)}{2}} \underbrace{\left(|h_1|^2 + |h_2|^2\right)}_{\text{Diversity = 2}} b_i(k) + \eta_i \quad \underset{b_i(k)=-1}{\overset{b_i(k)=+1}{\gtrless}} \quad 0$$

Practical Considerations

Assumptions So Far

- Synchronous system
- Orthogonal Code Sequences
- Frequency non-selective fading (no multipaths)

⇒ no inter-user interference

- Perfect channel estimates

In a Realist Scenario

- Frequency selective fading (multipaths)
- Imperfect channel estimates

System Performance

- With multipath components and no other user
- With multipath components and other users

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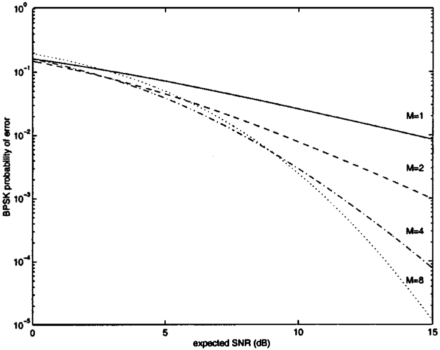
Effect of Channel Estimation Error

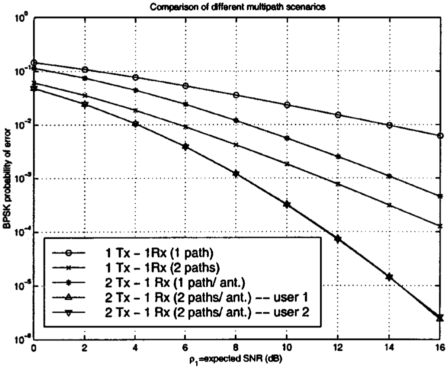


Probability of error for BPSK modulation vs. expected message SNR for 1, 2, 4 and 8 antennas, where errors in estimating the propagation coefficients are accounted for; total pilot power is 10 dB stronger than the total message power for each user i.e. $E_p = 10E_b$.

$$P_e = \frac{1}{(4+4\beta)^M} \sum_{j=0}^{M-1} \frac{\Gamma(2M-1-j)}{\Gamma(M)\Gamma(M-j)} \left[\frac{2\sqrt{4+4\beta}}{\sqrt{4\beta}+\sqrt{4+4\beta}} \right]^{1+j}$$

$$\text{where} \quad \beta = \frac{E_p E_b}{N_0 M (N_0 M + E_p + E_b)}$$

Effect of Multipath (Single User)



Probability of error for BPSK modulation vs. expected message SNR for 1 and 2 transmit antennas in flat fading and in multipath with perfect knowledge of fading coefficients. Codes $\boldsymbol{c}_1$ and $\boldsymbol{c}_2$ are Walsh codes of length 128 and delay between two paths is 10 chips.

$$P^{(1)}_{e|H} = \frac{1}{2} Q\left[\mathrm{Re}\{g_{11} + g_{12}\}\sqrt{\frac{E_b}{N_0 g_{11}}}\right] + \frac{1}{2} Q\left[\mathrm{Re}\{g_{11} - g_{12}\}\sqrt{\frac{E_b}{N_0 g_{11}}}\right]$$

$$P^{(2)}_{e|H} = \frac{1}{2} Q\left[\mathrm{Re}\{g_{22} + g_{21}\}\sqrt{\frac{E_b}{N_0 g_{22}}}\right] + \frac{1}{2} Q\left[\mathrm{Re}\{g_{22} - g_{21}\}\sqrt{\frac{E_b}{N_0 g_{22}}}\right]$$

What is Missing?

- Accepted as optional diversity mode in release A of IS-2000 wideband CDMA standard
- Effect on performance of other user interference

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Multiuser Interference

System

- Two transmit antennas — one receive antenna
- J multipaths from each antenna
- BPSK modulation
- Each user is modulated using a random carrier phase
- Coherent demodulation

Assumptions

1. Each path experiences independent Rayleigh fading
2. Multipath delay an integral multiple of chip interval
3. Same set of delays from both transmit antennas
4. Intersymbol interference can be neglected

Bound on Probability of Error

$$P_{e|H}^{(1)} \le \min_{\rho>0} \mathbb{E}\left\{ \begin{array}{c} \exp\left(\rho\sqrt{\frac{E_c(1)}{2}}\tilde{g}_{1,1}(1)b_1(1)\right)\exp\left(\rho\sqrt{\frac{E_c(1)}{2}}g_{1,2}(1)b_2(1)\right) \\ \times \prod_{k=2}^{K_u}\prod_{i=1}^{2}\exp\left(\rho\sqrt{\frac{E_c(k)}{2}}\tilde{g}_{1,i}(k)b_i(k)\cos\theta_k\right)\exp\left(\rho\eta_1\right) \end{array} \middle| \begin{array}{c} \boldsymbol{b}_1(1) = -1 \\ \boldsymbol{h}_1, \boldsymbol{h}_2 \end{array} \right\}$$

$$\mathbb{E}\left\{\exp\left(\rho\sqrt{\frac{E_c(1)}{2}}\tilde{g}_{1,1}(1)b_1(1)\right)\right\} = \exp\left(-\rho\sqrt{\frac{E_c(1)}{2}}g_{1,1}(1)\right)$$

$$\mathbb{E}\left\{\exp\left(\rho\sqrt{\frac{E_c(1)}{2}}g_{1,2}(1)b_2(1)\right)\right\} \le \exp\left(\rho\sqrt{\frac{E_c(k)}{2}}\left|\tilde{g}_{1,2}(1)\right|\right)$$

$$\mathbb{E}\left\{\exp\left(\rho\sqrt{\frac{E_c(k)}{2}}\tilde{g}_{1,i}(k)b_i(k)\cos\theta_k\right)\right\} \le ?$$

$$\mathbb{E}\left\{\exp\left(\rho\eta_1\right)\right\} = \exp\left(\frac{1}{2}\rho^2 g_{1,1}(1)\frac{N_0}{2}\right)$$

Bound on Probability of Error

$$P_{e|H}^{(1)} \leq \min_{\rho>0} \mathbb{E}\left\{ \begin{array}{c} \exp\left(\rho\sqrt{\frac{E_c(1)}{2}}\tilde{g}_{1,1}(1)b_1(1)\right)\exp\left(\rho\sqrt{\frac{E_c(1)}{2}}g_{1,2}(1)b_2(1)\right) \\ \times\prod_{k=2}^{K_u}\prod_{i=1}^{2}\exp\left(\rho\sqrt{\frac{E_c(k)}{2}}\tilde{g}_{1,i}(k)b_i(k)\cos\theta_k\right)\exp\left(\rho\eta_1\right) \end{array} \middle| \begin{array}{c} \boldsymbol{b}_1(1) = -1 \\ \boldsymbol{h}_1, \boldsymbol{h}_2 \end{array} \right\}$$

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Fixed Codewords for All Users

$$\mathbb{E}\left\{\exp\left(\rho\sqrt{\frac{E_c(k)}{2}}\tilde{g}_{1,i}(k)b_i(k)\cos\theta_k\right)\right\} \leq \exp\left(\frac{1}{4}\rho^2\frac{E_c(k)}{2}\left(\tilde{g}_{1,i}(k)\right)^2\right)$$

$$P_{e|H}^{(1)} \leq \exp\left\{-\frac{\left(\sum_{j=1}^{J} h_{1,j}^2+\sum_{j=1}^{J} h_{2,j}^2\right)\frac{E_b(1)}{2}\left[1-\left|\frac{g_{12}(1)}{g_{11}(1)}\right|\right]^2}{\frac{1}{2Ng_{11}(1)}\sum_{k=2}^{K_u}\frac{E_c(k)}{2}\left((g_{1,1}(k))^2+(g_{1,2}(k))^2\right)+N_0}\right\}$$

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Averaged over All Codewords

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$$P_{e|H}^{(1)} \leq \exp\left\{-\frac{\left(\sum_{j=1}^{J}h_{1,j}^2+\sum_{j=1}^{J}h_{2,j}^2\right)\frac{E_b(1)}{2}\left[1-\left|\frac{g_{12}(1)}{g_{11}(1)}\right|\right]^2}{\frac{1}{2N}\left(\sum_{j=1}^{J}h_{1,j}^2+\sum_{j=1}^{J}h_{2,j}^2\right)\sum_{k=2}^{K_u}\frac{E_b(k)}{2}+N_0}\right\}$$

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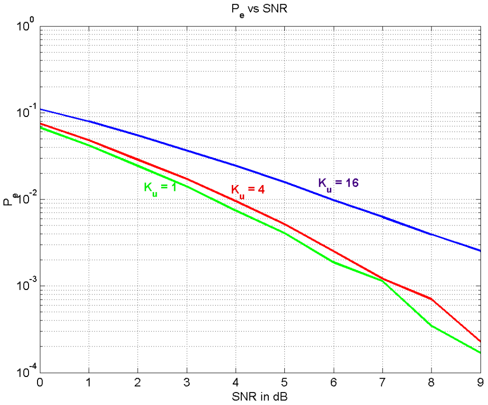

- P_e vs SNR for $K_u = 1$, $K_u = 4$ and $K_u = 16$
- Walsh Code of length $2N = 128$
- $J = 2$ multipaths
- Path delay, $\tau = 10$ chips
- Rayleigh fading
- Perfect CSI available

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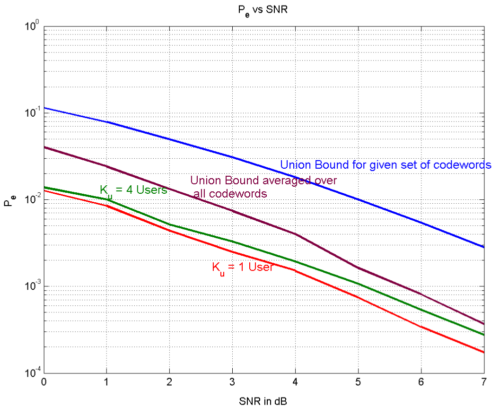
Bound vs Performance



- P_e vs SNR for $K_u = 1$ and $K_u = 4$, union bound for given set of codes and union bound averaged over all codes
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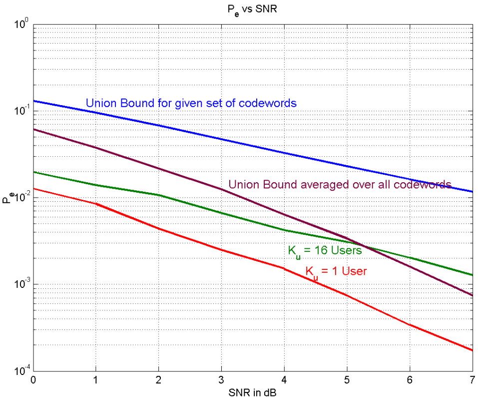
$$P^{(1)}_{e|H} \leq \exp\left\{ - \frac{\left(\sum_{j=1}^{J} h^2_{1,j} + \sum_{j=1}^{J} h^2_{2,j}\right) \frac{E_b(1)}{2} \left[1 - \left|\frac{g_{12}(1)}{g_{11}(1)}\right|\right]^2}{\frac{1}{2Ng_{11}(1)} \sum_{k=2}^{K_u} \frac{E_c(k)}{2}\left((g_{1,1}(k))^2 + (g_{1,2}(k))^2\right) + N_0} \right\}$$

Bound vs Performance



- P_e vs SNR for $K_u = 1$ and $K_u = 16$, union bound for given set of codes and union bound averaged over all codes
- Walsh Code of length $2N = 128$
- $J = 2$ multipaths
- Path delay, $\tau = 10$ chips
- Rayleigh fading
- Perfect CSI available

$$P_{e|H}^{(1)} \leq \exp\left\{ - \frac{\left(\sum_{j=1}^{J} h_{1,j}^2 + \sum_{j=1}^{J} h_{2,j}^2 \right) \frac{E_b(1)}{2} \left[1 - \left| \frac{g_{12}(1)}{g_{11}(1)} \right| \right]^2}{\frac{1}{2Ng_{11}(1)} \sum_{k=2}^{K_u} \frac{E_c(k)}{2} \left((g_{1,1}(k))^2 + (g_{1,2}(k))^2 \right) + N_0} \right\}$$

Outline

Conclusion

Space Time Spreading

1. Provides optimal two-fold diversity
2. Rate = 1 scheme
3. Requires linear complexity receiver
4. No extra spreading codes required
5. Acceptable performace in MAI.

Thank You