Capacity Enhancement Methods for Wireless Networks

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Outline

- Introduction and Motivation
- Wireless Channels:
  - Fading, diversity
  - Transmission model, Multiple Antenna Systems, Capacity
- Space-Time Codes
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  - Space-Time Trellis Codes
- Differential Detection Transmit Diversity
- Combined STC and Signal Processing Techniques
- System Impact

Outline

- Review of Beamforming
  - Complementary Beamforming
- Distributed Space-Time Communications

Introduction

Motivation

- Wireless communications has seen enormous growth in the past decade and this growth is anticipated to continue.
- It is projected that the number of wireless subscribers will exceed that of wire-line subscribers. We are experiencing
  - Rapid Growth in wireless services,
  - Rapid Convergence with the Internet (Both in Cellular and WLANs).

Wireless Applications

- Mobile Telephony/data/multimedia (3G)
- Wireless LANs (IEEE 802.11)
- Digital Broadcasting (DAB, DVB)
- Bluetooth
- Wireless Local Loops
- Wireless Internet/m-commerce
- Localization

Wireless LANs

- Wireless LANs provide short range high speed data appropriate for hot spots.
- The key to their success is their inexpensiveness (for home applications) and lack of cost for the underlying spectrum.
- When networking this solution for large businesses the cost may become expensive. In other words, Wireless LANs do not scale trivially.
- Free spectrum make co-existence an issue.

Wireless LANS

- They suffer from poor adjacent channel rejection and transmit mask
- Nevertheless, the inexpensiveness and availability for reasonable short range data rates makes them very useful
- This has motivated research to increase the range and data rates of IEEE WLANs.
- This is a challenging task given the limitations of wireless channels.

Wireless Challenges

- High Data Rate (multimedia traffic)
- Networking (seamless connectivity)
- Resource Allocation (quality of service-QOS)
- Mobility (rapidly changing physical channel)
- Portability (battery life)
- Privacy/Security (encryption)

Limitations

- Channel Limitations
  - Path Loss, Shadowing, Fading (data rates depend on time, frequency and space).
  - Limited Spectrum
  - Dynamism (random access, mobility)
  - Interference
- Device Limitations
  - Limited Battery Power
  - Limited Size of Devices
  - Limited Computation Power of Devices
  - Non-ideal Hardware Characteristics (e.g. non-linearities, etc.)

- Man Made Limitations
  - Limitation on Transmit Power
  - Co-existence issues
  - Limitations on consumer tolerance to lack of quality
- With all the above impairments, a fat data pipe is hard to make.
- Thus we need to consider new technologies to increase the range/data rates of wireless systems.

Enabling Technologies

- Resource manangement becomes extremely important in order to provide QOS.
- Air interface: OFDM, CDMA, TDMA, etc.
- Signal Processing: Source/Channel Coding, MIMO (Space-Time Coding, Beamforming, collaborative space-time communications), Multiuser detection (MUD)
- All of the above issues warrant a lot of attention

Signal Processing to Rescue

- The good news is that the computation power of signal processors is increasing very rapidly.
- This means that we can implement a lot fancier algorithms than before.
- These algorithms include
  - Source and Channel Coding
  - Space-time coding
  - Beamforming (including complementary beamforming)
  - Multiuser detection (MUD) and MIMO-MUD
- All these techniques produce a variety of advantages in different situations.

MIMO Technologies

MIMO Technologies

- MIMO Technologies are divided into three groups:
  - Space-time coding (including collaborative space-time coding)
  - Beamforming (including complementary beamforming)
  - Hybrid Methods
- All require multiple antennas at either the transmitter and/or the receiver.

Fading, Diversity

- Scattering, Rayleigh fading, shadowing, path loss.
- Deep fade → Another Replica of the transmitted signal must be sent to the receiver in another format = Diversity.
- Diversity:
  - Temporal diversity (well understood),
  - Frequency Diversity (well understood),
  - Spatial (Antenna) Diversity
    - receive antenna diversity (well understood).
    - transmit antenna diversity (subject of current research).

Space-Time Coding

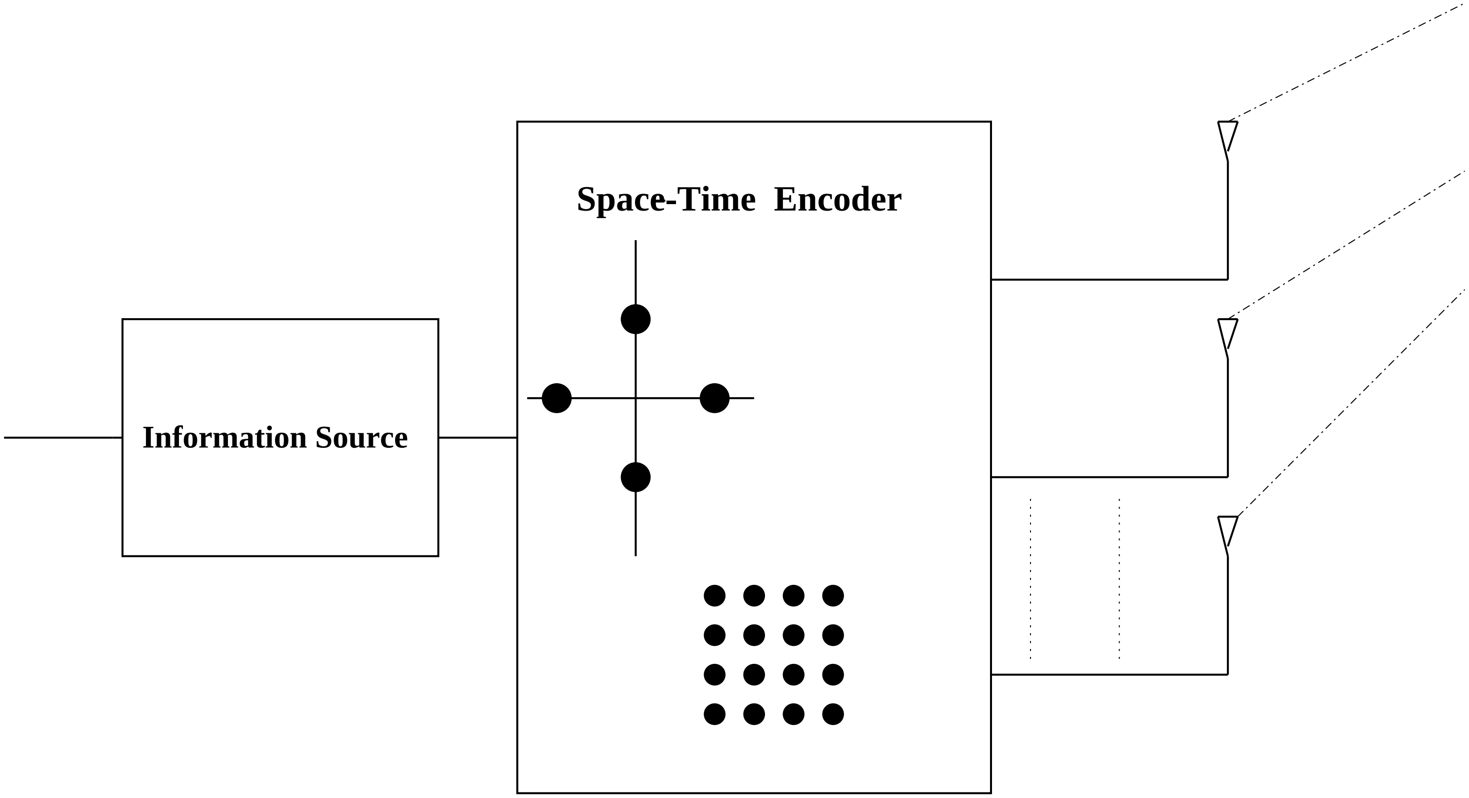
Space-Time Coding

- Assumes no knowledge of channel at the transmitter (with the option of no channel state information at the receiver)
- Provides antenna diversity to combat fading.
- STC exploits two resources:
  - Receive antenna diversity
  - transmit antenna diversity

Multiple Antenna System Model

- There are N transmit and M receive antennas.
- At each time, N signals are transmitted at the same time each from a different transmit antenna.
- These signals have the same transmission period.
- Signals transmitted from different antennas undergo independent fades.
- The received signal at each receive antenna is a linear superposition of the transmitted signals perturbed by noise.

Main Idea



MIMO Channel Model

- Mathematically, if $s_{t,n}$ is transmitted from antenna n, the signal $r_{t,m}$, received at antenna m is given by

$$r_{t,m} = \sum_{n=1}^{N} \alpha_{n,m} s_{tn} + \eta_{t,m}.$$

- The path gain $\alpha_{n,m}$ is the path gain from transmit antenna n to receive antenna m. Here a flat fading and quasi-static channel was assumed.
- In recent years, a lot of work has been done on the modeling the MIMO channels.

Capacity of MIMO Systems

- Telatar, and independently Foschini and Gans have considered the capacity of a multiple antenna system with N transmit and $M = N$ receive antennas.
- They proved that:

The Capacity Increases Linearly as a function of N as $N \to \infty$.

- How to exploit this capacity?

Space-Time Codes

Space-Time Codes

- The way to achieve the capacity of a communication channel is by coding and signal processing.
- Space-Time codes are coding schemes appropriate to multiple antenna systems.
- Their mathematical design theory is complicated and will not be discussed in this presentation.

Space-time Codes–Early Developments

- Capacity of Multiple Antenna Systems, (Foschini and Gans)
- Space-Time Trellis Codes [TSC]
- Space-Time Block Codes [A, TJC]
- Combined STC and Signal Processing Techniques [TNSC]
- Differential Detection Transmit Diversity [TJ]
- System Impact (AT&T Research, Ericsson Research)

Design Criteria

- Any code must be designed based on a design criteria. For example:
  - For Gaussian channels, the distance between the codewords must be maximized.
  - For some channels, Hamming distance must be maximized.
- Is there a specific design criteria for designing space-time codes?
- Answer: yes!, and it is complicated.

Design Criteria For STC

- For any two space-time codewords $C_1 \neq C_2$,
  - The error matrix $C_1 - C_2$ has to be full rank in order to obtain diversity NM.
  - The determinant of $(C_1 - C_2)^*(C_1 - C_2)$ has to be large.
- This is a complicated design criteria!
- The designed codes must be simple to encode and decode as well!.

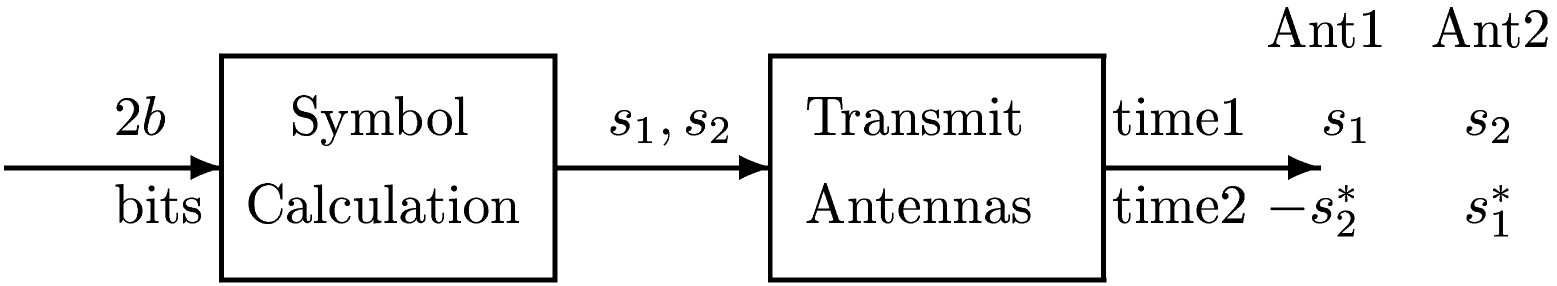
Space-Time Block Codes

STBC

- An interesting solution is given by space-time block codes.
- We motivate by a simple example for two transmit antennas.
  - Suppose the signal constellation has 2^b elements. example: BPSK, QPSK, 8-PSK, 16-QAM
  - At time one, $2b$ bits arrive at the encoder and pick up constellation symbols s_1 and s_2.
  - The transmission matrix is then:

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}.$$

STBC: 2 Tx



$2b$ bits

Symbol Calculation

s_1, s_2

Transmit Antennas

	Ant1	Ant2
time1	s_1	s_2
time2	$-s_2^*$	s_1^*

Figure 1: Transmitter Block Diagram.

Maximum Likelihood Decoding

- If the constellation has equal energy the ML decoding is given by:

$$\left|[\sum_{m=1}^{M}(r_{1,m}\alpha_{1,m}^{*}+r_{2,m}^{*}\alpha_{2,m})]-s_1\right|$$

for decoding s_1 and

$$\left|[\sum_{m=1}^{M}(r_{1,m}\alpha_{2,m}^{*}-r_{2,m}^{*}\alpha_{1,m})-s_2\right|$$

for decoding s_2.

Remarkable Properties

- **Simple decoding:** Each symbol is decoded separately using only linear processing.
- **Maximum diversity:** Same performance as a two-level maximum ratio combining.

Is it possible to design similar codes for more number of transmit antennas?

Orthogonal Designs

- What is the reason for getting these properties?

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}$$

- The columns of **S** are orthogonal to each other:

$$\mathcal{S}^*\mathcal{S} = (|s_1|^2 + |s_2|^2)I.$$

- We call such a **S** an orthogonal design.
- Using this theory, we could design space-time block codes for any number of transmit antennas.

Example

- $K = 3,\ L = 8,\ N = 4,\ R = 0.5$

$$\begin{pmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2 & s_1 & -s_4 & s_3 \\ -s_3 & s_4 & s_1 & -s_2 \\ -s_4 & -s_3 & s_2 & s_1 \\ s_1^* & s_2^* & s_3^* & s_4^* \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & s_4^* & s_1^* & -s_2^* \\ -s_4^* & -s_3^* & s_2^* & s_1^* \end{pmatrix}$$

Example

- $K = 4,\ L = 8,\ N = 3,\ R = 0.5$

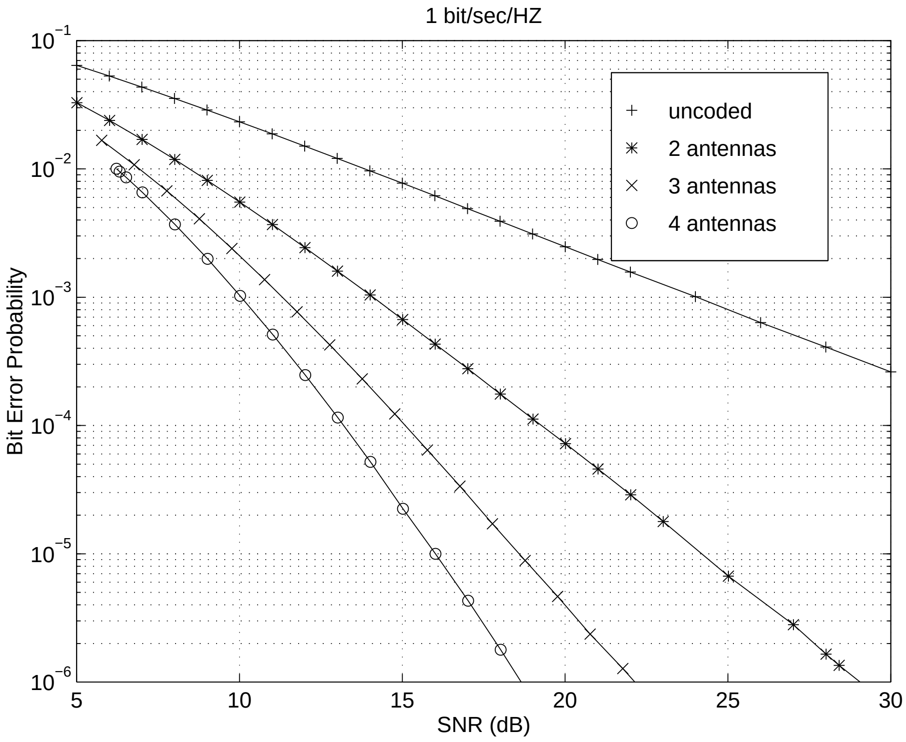
$$\begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2 & s_1 & -s_4 \\ -s_3 & s_4 & s_1 \\ -s_4 & -s_3 & s_2 \\ s_1^* & s_2^* & s_3^* \\ -s_2^* & s_1^* & -s_4^* \\ -s_3^* & s_4^* & s_1^* \\ -s_4^* & -s_3^* & s_2^* \end{pmatrix}$$

Example

- $K = 3,\ L = 4,\ N = 4,\ R = 0.75$

$$\begin{pmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ s_3^* & 0 & -s_1^* & s_2 \\ 0 & s_3^* & -s_2^* & -s_1 \end{pmatrix}$$

Simulation Results



Conclusions

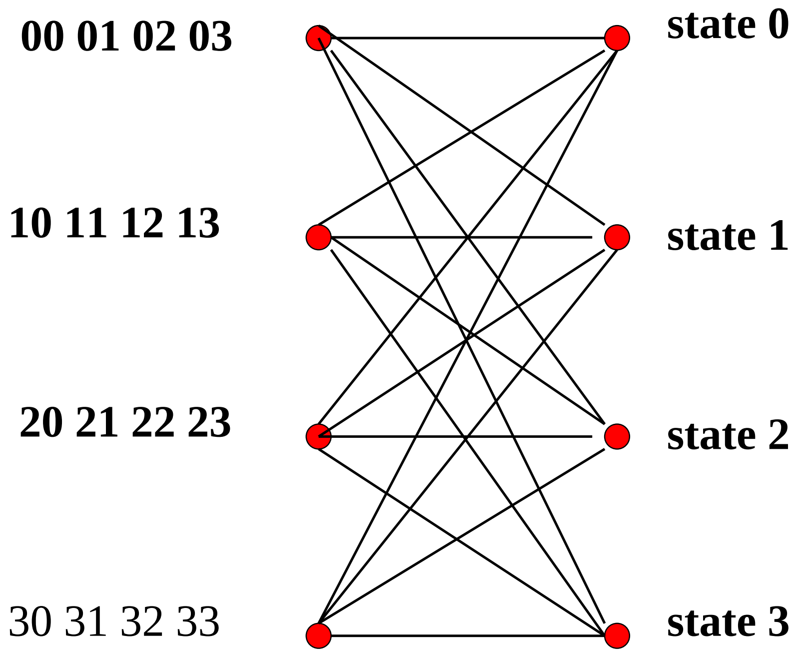
- Space-time block coding is a simple technique for achieving diversity on MIMO wireless channels.
- Space-time block codes from orthogonal designs provide maximum diversity and enjoy simple encoding/decoding.
- Real constellation space-time block codes can provide maximum possible diversity and rate for any number of transmit antennas.
- Rate half complex constellation space-time block codes can provide maximum possible diversity for any number of transmit antennas
- Rate 3/4 complex space-time block codes which provide maximum possible diversity for $N = 3, 4$ and rate one code for $N = 2$ also exist.

Space-Time Trellis Codes

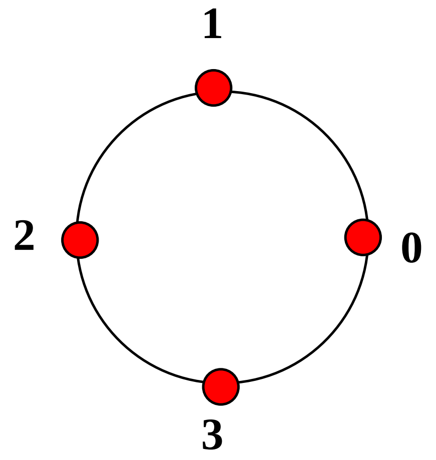
Motivation

- It is possible to design trellis codes using the space-time design criteria.
- We have done this for BPSK, QPSK and 8-PSK, 16-QAM constellations.
- In designing these codes, the trade-offs between constellation size, diversity, number of states of the trellis and data rate have been studied.
- The codes that we will present optimize these trade-offs.

Example: QPSK; 2 Tx; 4 States



4 State QPSK Space-Time Code



QPSK Signal Constellation

Encoding

- The encoding always starts at state S_0.
- At each time t, the encoder is at state S_t.
- Each time 2 bits arrive at the encoder.
- These two bits choose one of the four branches originating from S_t.
- The two labels of that branch are sent from Tx antennas 1 and antenna 2 simultaneously.
- The encoder moves to the state S_{t+1} at the end of that chosen branch.

Decoding

- Decoding is done using the Viterbi algorithm.
- Suppose that the received word at time t at Rx antenna m is $r_{t,m}$.
- For each branch labeled c_1c_2 the branch metric is given by

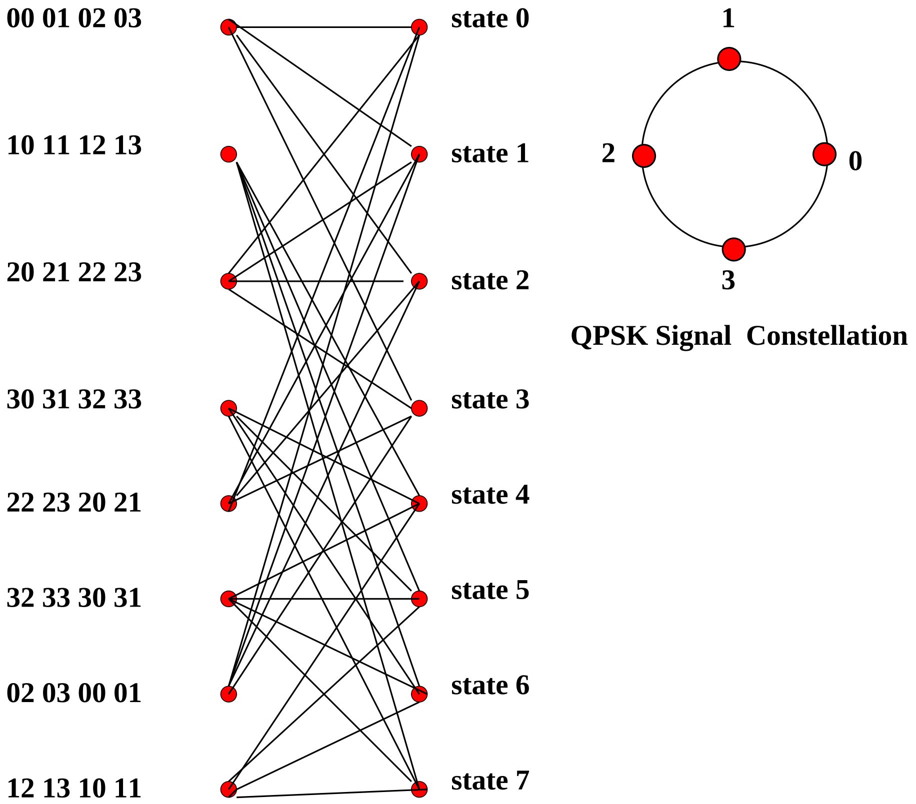
$$\sum_{m=1}^{M} |r_{t,m} - \alpha_{1,m}c_1 - \alpha_{2,m}c_2|^2$$

- The path through the trellis with minimum total metric is computed using the Viterbi algorithm.

Decoding

- In general, the decoding complexity of Space-Time Trellis Codes are almost the same as trellis codes used over Gaussian channels with the same number of states.
- The encoding complexity of Space-Time Trellis Codes are the same as trellis codes used over Gaussian channels with the same number of states.
- Space-Time Trellis codes are easily implementable.
- They achieve full spatial diversity.
- It is possible to improve their performance by increasing the number of states of the trellis.

Example: QPSK; 2 Tx; 8 states



QPSK Signal Constellation

Conclusions

- STTC for MIMO channels are like Ungerboeck's trellis codes for Gaussian channels.
- Encoding is simple and decoding is done using the Viterbi algorithm.
- The decoding and encoding complexities of Space-Time Trellis Codes are almost the same as trellis codes used over Gaussian channels with the same number of states.
- Space-Time Trellis codes are easily implementable.
- They achieve full spatial diversity.
- It is possible to improve their performance by increasing the number of states of the trellis.

Differential Detection Transmit Diversity

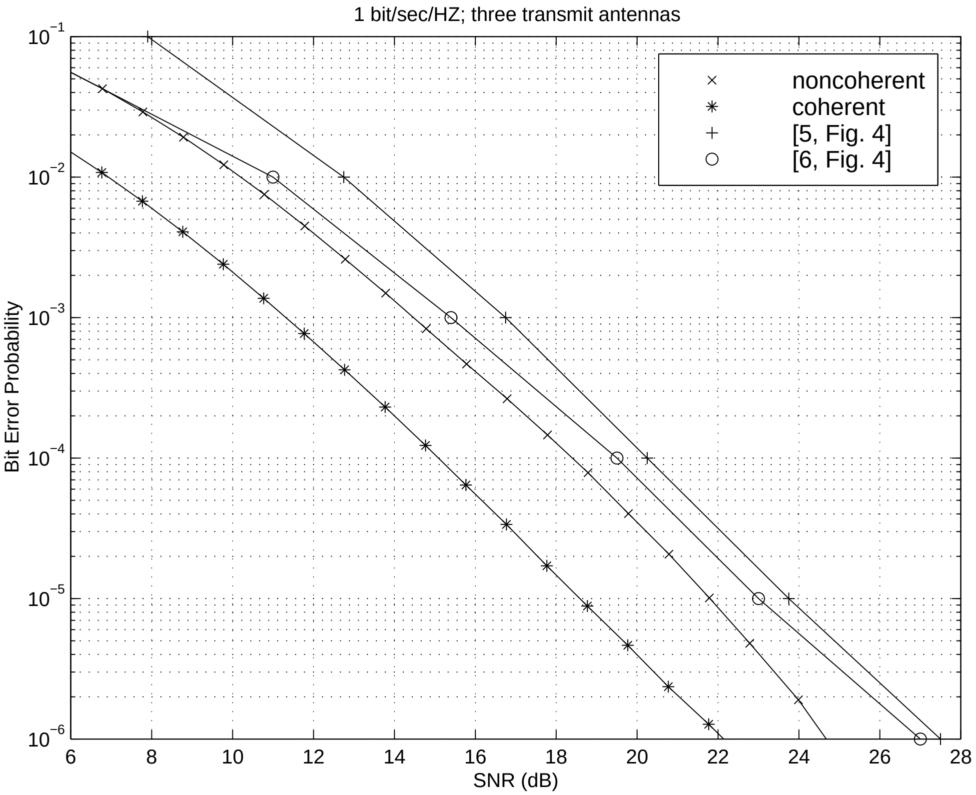
Motivation

- The above space-time block codes and space-time trellis codes are designed assuming that the receiver (but not the transmitter) has knowledge of the channel coefficients.
- This can be achieved by sending pilot signals.
- It is also true in most applications as the receiver has to estimate the channel for many other reasons.
- However, in some applications, it may be desired that the receiver avoids channel estimation.
- For one transmit and one receive antenna systems, DPSK algorithms are well-known.
- A method for multiple antenna differential detection is presented in [TJ].

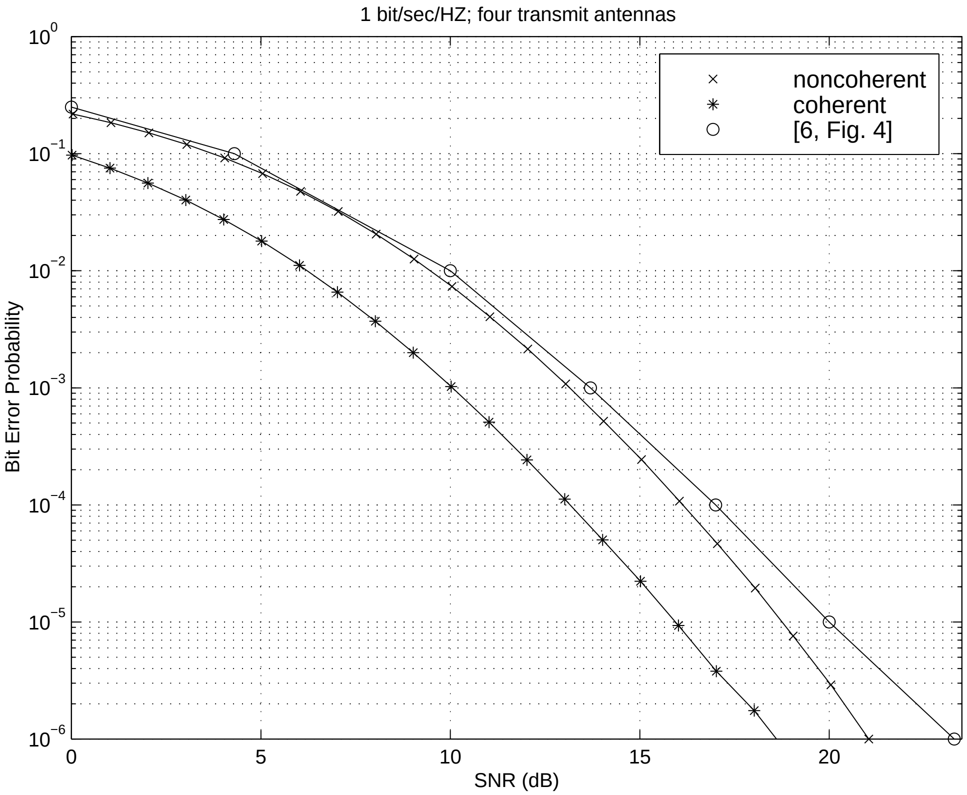
Differential Detection (DPSK)

- This method provides full antenna diversity.
- Encoding and Decoding are very simple.
- generalizes standard (SISO) differential detection, and
- Performance of the scheme is 3 dB worse than that of coherent detection (space-time block coding).
- It can be used with any number of transmit antennas.

Simulation Results



Simulation Results



Combined STC and Signal Processing Techniques

Combined STC and Array Processing

Combined Array Processing and Space-Time Coding

- We can use the above technique to boost the data rates of multiple antenna systems [TNSC].
- We trade: diversity for data rate.
- This can be used to boost the data rates of multiple antenna wireless communication systems.

Combined Array Processing and STC

- Scenario: N transmit antennas and M receive antennas
- We divide N transmit antennas into groups of N_1, $N_2, \cdots, N_k$ antennas.
- Each group of N_i transmit antennas are employed to transmit using a space-time code $\mathcal{C}_i$.
- At the receiver $N - N_i$ dimensions provided by receive antennas are used to suppress the transmission from other groups.
- It is shown in [TNSC], In detection of $\mathcal{C}_i$, we get the same performance as a system with N_i Tx antennas and $M - N + N_i$ Rx antennas that uses the space-time code $\mathcal{C}_i$ for transmission.
- This gives a huge boost in data rate and also provides diversity.
- It can proved that this technique is capacity achieving.

Combined STC and Interference Suppression

Combined STC and Interference Suppression

- Interference suppression techniques can be combined with ST-coding.
- We will discuss this combination for two cases:
  - Case I: Synchronous Interference
  - Case II: Asynchronous Interference
- First we will review the results.

Overview: Synchronous Interferer

- Scenario: K transmitters, N transmit antennas per transmitters.
- Classical IC techniques need $N(K-1)+1$ receive antennas to suppress int erference from $K-1$ co-channel transmitters.
- With STBC, we can use the structure of the code to suppress interference: Only K receive antennas are required and N level Tx diversity is achieved.
- This suppression method can also be adaptively implemented (adaptive LMS or RLS).
- This can be used to increase the data rate or capacity.

Asynchronous Interferer

- Scenario: K transmitters, N transmit antennas per transmitters.
- A Receiver with M receive antennas, where $M \geq N(K-1)+1$.
- The receiver uses $N(K-1)$ of receive antennas to suppress signals of the interfering transmitters.
- This gives diversity $N(M-NK+K)$ for the desired transmitters.

System Impacts

System Impacts

- Physical layer techniques do not mean much if the overall system capacity does not improve.
- For various TDMA systems, it was shown that STC codes for 2 Tx chains can increase the capacity by about 60% (Winters, Clark).
- Ericsson Researchers have shown that the capacity of WCDMA systems (UMTS) increases (by about the same amount) using STC codes and 2 Tx chains.

Beamforming and Complementary Beamforming

Directional Signals

- In most wireless networks, data-bearing signals are intended to travel between two nodes; typically a central node and a portable or mobile node.
- In such networks, it is inefficient to transmit a signal in all directions. The energy in all directions except in the direction of the desired node is wasted.
- → Directional signals can make a big difference in the efficiency and performance of wireless networks.

Directional Signals

- In fact, using directional signals (beams), it is possible to increase the range or capacity of any wireless link without changing the air-interface or even increasing the transmit power.
- This is done by focusing the energy in the direction of desired receivers (nodes) using antenna arrays and beamforming networks.
- As a result, there has been great interest in using directional signals to improve the performance of wireless systems.
- In fact, most commercial mobile radio networks employ sectorization which is a simple form of directional signal transmission.

Beamforming and Backward Compatibility

- If scheduled correctly, directional beams reduce overall interference in the network.
- Thus beamforming/SDMA can be an appealing interim solution for increasing range and data rates of current WLAN standards since no change to air-interface and receiver is needed.
- In contrast, space-time coding requires changes to existing WLAN standards.

Beamforming

- Requires the knowledge of the channel at the transmitter or some knowledge of relative direction between the receiver and transmitter.
- This information can be derived at the transmitter using:
  - Dedicated feedback channel (overhead is needed)
  - From the uplink transmission (in some cases). In this case, one must compensate for the characteristic differences between receiver and transmitter chains (hard to do but not impossible).

Beamforming

- Fixed beams ae easier to implement in nomadic situations (such as typical WLAN deployment scenarios)
- SDMA is harder to implement in packet based systems.
- Channel estimation is an important problem.
- In receiver SDMA, an intercepting packet can seriously degrade the performance.
- In some cases, it is hard to acknowledge shorter packets until the longer packets are received and this may cause an ACK time-out.
- Interference can seriously affect the performance of beamforming.

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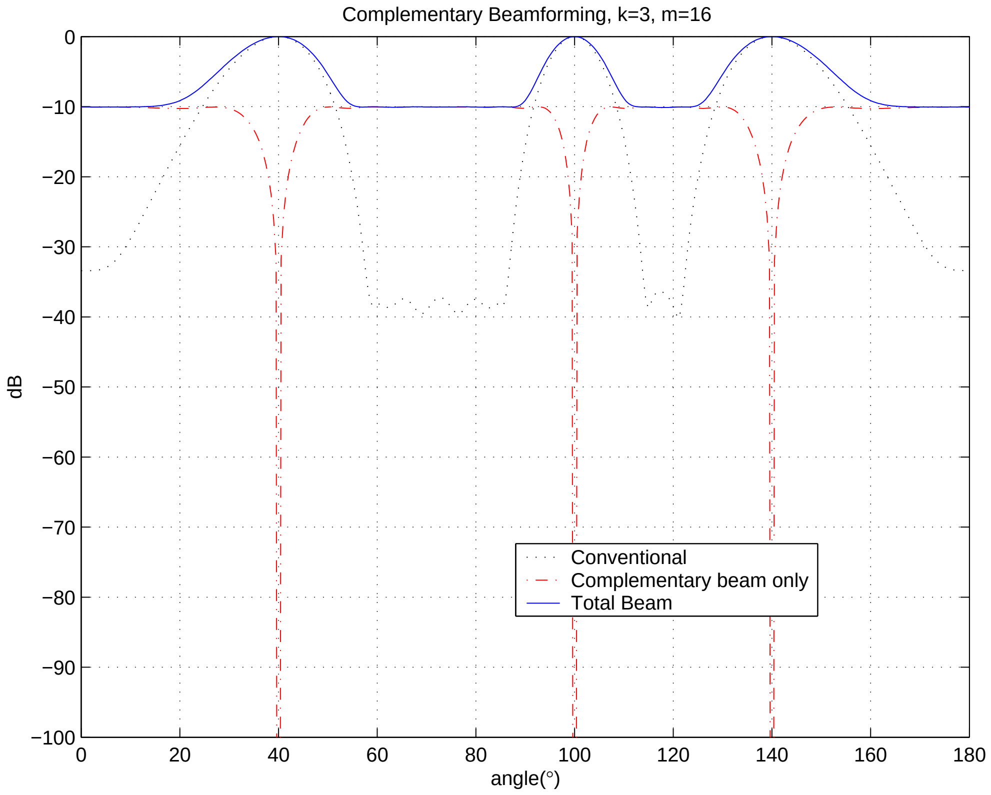
CSMA and Beamforming

- The combination of beamforming/SDMA and CSMA has not been extensively researched before.
- Beamforming in combination with carrier sensing can be problematic.
- By pointing the power in some directions, a potential side-effect can be the hidding of the transmitted signals from some nodes in the network.
- We refer to this problem as the *hidden beam problem.*

CSMA and Beamforming

- In CSMA, a given node listens for energy from other nodes in the network.
- If it cannot detect the presence of other transmissions, it attempts to gain access to the medium.
- In this light, the hidden beam problem may cause unnecessary transmissions and back-offs which negatively impact the performance of the network.
- In other words, in channel sensing networks, every transmission carries some useful information for all the nodes in the network. The transmitted signal carries data to its target node, and also informs the rest of the nodes in the network not to transmit.
- Therefore, beamforming can potentially destroy some valuable information intended for some nodes.

Time Domain CBF



CSMA and Beamforming

- Fortunately, in practice, directional signals are not “pencil beams”. They generally have a main lobe whose width is constrained by the antenna structure, and sidelobes whose levels vary in different directions.
- Nevertheless, these beams may have deep nulls in some directions. In these directions, the network will suffer from the *hidden beam problem.*
- For these networks to operate efficiently, we would like
  - the desired (active) nodes to have sufficient signal to interference and noise ratio (SINR) to decode the data and
  - at the same time for the rest of the nodes (passive nodes) to receive sufficient energy to refrain from transmission.

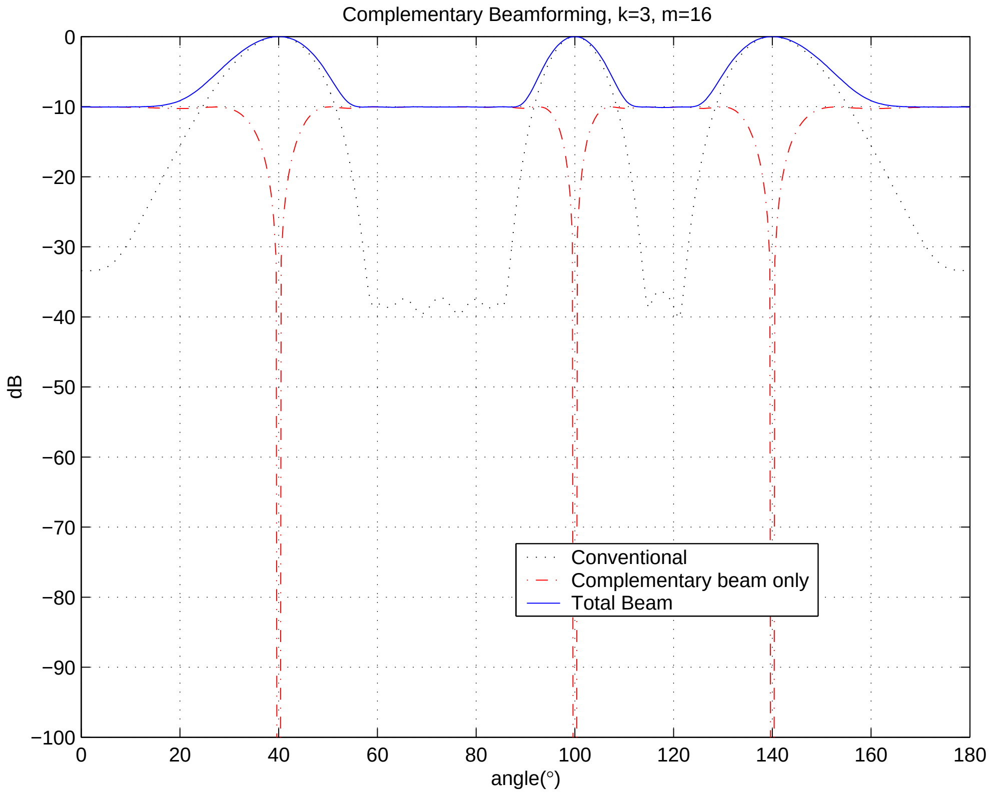
Complementary Beamforming

- In an ideal scenario, we would like to
  - establish simultaneous spatial links to active nodes using Space Division Multiple Access (SDMA) and
  - a broadcast link to the rest of the nodes in the network (passive nodes).
  - The broadcast link must not interfere with the data bearing beam (spatial links).
- The concept of transmitting data in one or more simultaneous beams combined with a broadcast signal (whether a non-data-bearing energy signal or an actual data-bearing signal) to all other directions (herein referred to by the *Complementary Region*) is what we have termed complementary beamforming.

Complementary Beamforming

- Clearly, the detection of busy period is easier than decoding of transmitted packet and this is exploited in many systems (for example the IEEE 802.11 WLANs).
- Typically, in wireless CSMA systems, each device listens to the channel during some time window and compares the energy collected in this window to a CCA (Clear Channel Assessment) threshold.
- Detect activity: if the collected energy $\geq$ the CCA threshold.
- The CCA threshold is much lower than the SINR required for decoding.
- → The complementary beam needs to be some orders of magnitude less powerful than the data bearing signal.

Time Domain CBF



Notation

- For any vector X, we let X^T and X^H respectively denote the transpose and Hermitian of X.
- For any matrix D, we let W_D denote the vector space spanned by the columns of D.
- Let the channel from transmit antenna l to the intended user j be given by $\alpha_{l,j}$.
- Let A_j denote the column vector $(\alpha_{1,j}, \alpha_{2,j}, \cdots, \alpha_{m,j})^T$. We refer to the vector A_j as the *spatial signature of user j*.
- Let A denote the matrix whose j-th column is A_j.

Notation

- Let $R^t = (r_1^t, r_2^t, \cdots, r_k^t)$ and $X^t = (x_1^t, x_2^t, \cdots, x_m^t)$ respectively denote the vector of received signals at intended users $j = 1, 2, \cdots, k$ and the vector of signals transmitted from antennas $1, 2, \cdots, m$ at time t.
- Let $C^t = (c_1^t, c_2^t, \cdots, c_k^t)$, where c_j^t is the signal intended to the $j = 1, 2, \cdots, k$ desired user at time t.
- For any square matrix A, let $Tr(A)$ denotes the trace (sum of diagonal elements of A).
- Let $N^t = (n_1^t, n_2^t, \cdots, n_m^t)$ be the noise vector components at time t at the intended users.

Beamforming Matrix

- Then

$$R^t = X^t A + N^t, \tag{1}$$

- Noise components are assumed to be i.i.d. Gaussian.
- *No assumptions* on the statistics of the matrix A.
- The signals c_j^t, $j = 1, 2, \cdots, k$, $t = 1, 2, \cdots, L$ are elements of a signal constellation with average signal $E[c_j^t] = 0$.
- The elements of the signal constellation are normalized so that their average power is $E[|c_j^t|^2] = 1$.
- In general $X^t = C^t \mathcal{B}$ where $\mathcal{B}$ is referred to as the *beamforming matrix.*

- Then for a *psuedo-inverse beamformer*

$$\mathcal{B} = \frac{(A^H A)^{-1} A^H}{\sqrt{Tr((A^H A)^{-1})}}$$

  and

- We present our technique for the psuedo-inverse beamformer here. Generalization to the maximum SINR case is obvious.
- We assume that the spatial signature matrix A is constant during the transmission of a packet.

Complementary Beamforming

- We seek a beam pattern such that the complementary beam does not interfere with the main beam (data-bearing signal).
- We first observe that the data bearing signal passes through the channel matrix A. Thus any perturbation in the transmitted signal vector X^t that lies in the nullspace (subspace orthogonal complement to the column space) of A, causes no interference to the received signal at the desired node.
- The converse is also true.
- Thus the entire complementary beam must be produced in the nullspace.
- To construct an omni-directional beam in complementary domain, these perturbations must be induced such that every dimension is ”covered” in the same manner.

Complementary Beamforming

- let W_A denote the vector space spanned by the columns of A.
- The subspace W_A is a k-dimensional subspace of the complex m-dimensional complex space
- Let $W_A^{\perp}$ be the orthogonal complement of W_A. $W_A^{\perp}$ has dimension $m-k$.
- Let $U_0, U_1, \cdots, U_{m-k-1}$ form an orthonormal basis for $W_A^{\perp}$.
- In other words, $U_0, U_1, \cdots, U_{m-k-1}$ are mutually orthogonal m-dimensional column vectors of length one in $W_A^{\perp}$.
- Clearly, $U_j^H A_i = 0$ for $0 \leq j \leq m-k-1$ and $1 \leq i \leq k$.

Complementary Beamforming

- The transmitter constructs matrices $Z_1, Z_2, \cdots, Z_L$, where L is the length of down-link transmission period, such that:
  - **A:** For all $1 \leq i \leq L$, the matrix Z_i is a $k \times m$ matrix whose rows are in the set $\{0, \pm U_0^H, \pm U_1^H, \cdots, \pm U_{m-k-1}^H\}$,
  - **B:** If L is even, then $Z_2 = -Z_1$, $Z_4 = -Z_3, \cdots, Z_L = -Z_{L-1}$,
  - **C:** If L is odd, then $Z_2 = -Z_1$, $Z_4 = -Z_3, \cdots, Z_{L-1} = -Z_{L-2}$, $Z_L = 0$, and
  - **D:** Each element

    $$+U_0^H, -U_0^H, +U_1^H, -U_1^H, \cdots, +U_{m-k-1}^H, -U_{m-k-1}^H$$

    appears p times in the the list of Lk rows of $Z_1, Z_2, \cdots, Z_L$ for some positive integer p.

Complementary Beamforming

- The construction of these matrices are easy and can be done in various ways. An straightforward construction is:
- For instance for even L, if we let $p = \lfloor Lk/2(m-k) \rfloor$, then we can assign U_j^H, $j = 0, 1, \cdots, (m-k-1)$ in sequential manner to the first p available columns of $Z_1, Z_3, \cdots$ and replace the remaining columns with zeroes. We then let $Z_2 = -Z_1$, $Z_4 = -Z_3, \cdots, Z_L = -Z_{L-1}$
- For odd L, we construct the $L-1$ matrices $Z_1, Z_2, \cdots, Z_{L-1}$ as above and let $Z_L = 0$.
- In both cases, we can guarantee that

$$\frac{Lk}{2(m-k)} \geq p \geq \lfloor \frac{k(L-1)}{2(m-k)} \rfloor \tag{2}$$

Complementary Beamforming

- Once $Z_1, Z_2, \cdots, Z_L$ are constructed, at each time t, the transmitter chooses the beamforming matrix

$$S^t = [((A^H A)^{-1} A^H / \sqrt{Tr((A^H A)^{-1})} + \frac{1}{\sqrt{k}} \epsilon Z_t], \qquad (3)$$

  where $\epsilon \geq 0$ is a fixed positive number.

- The choice of $\epsilon \geq 0$ governs the trade-off between the power pointed to the intended users and that pointed to unintended users.

- For $\epsilon = 0$, we recover the conventional beamforming → Complementary beamforming generalizes and includes conventional beamforming as a special case.

Analysis of CBF

Intended Users

- **Result:** Complementary beamforming to intended users has a loss of $10\log_{10}(1+|\epsilon|^2)$ dB when compared to the conventional method.

CBF: Silent Users

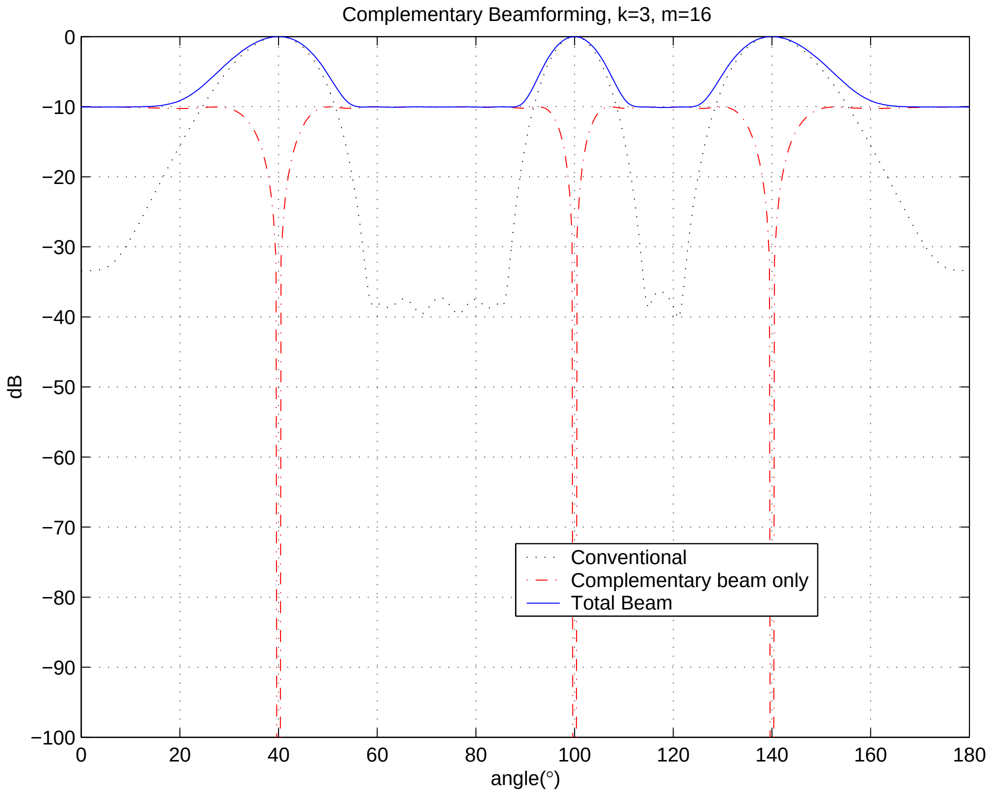
- **Result:** Let $\lambda_{\min}(A^H A)$ and $\lambda_{\max}(A^H A)$ respectively denote the minimum and maximum eigenvalues of $A^H A$. Then provided that

$$|\epsilon|^2 \le \frac{(m-k)}{k} \frac{\lambda_{\min}(A^H A)}{\lambda_{\max}(A^H A)}, \tag{4}$$

$$p \ge \frac{m}{k} - 0.5, \tag{5}$$

complementary beamforming guarantees a fraction $|\epsilon|^2 \frac{\sum_{j=1}^{m} |b_j|^2}{m}$ of the transmitted power to an unintended receiver whose spatial signature is $B = (b_1, b_2, \cdots, b_m)$.

Time Domain CBF



Network Issues

- Analysis show that the complexity of complementary beamforming is approximately twice as much as that of the conventional beamforming.
- It has been observed via simulations that using complementary beamforming significantly enhances the performance of a heavily loaded smart antenna enhanced CSMA systems compared to the case when conventional beamforming is employed.

Sending Data Using The Complementary Beam

- In the above construction the complementary beam did not carry any data information.
- In some applications, it may be desirable to transmit lower data rate control information to silent users.
- The complementary beam can be used for this purpose as described below.
- Recall that in the above complementary beamforming construction, p occurrences of U_j^H and p occurrences of $-U_j^H$ existed in the LK rows of Z_i, $i = 1, 2, \cdots, L$
- If we instead allow $2p$ occurrences of U_j^H with the sign

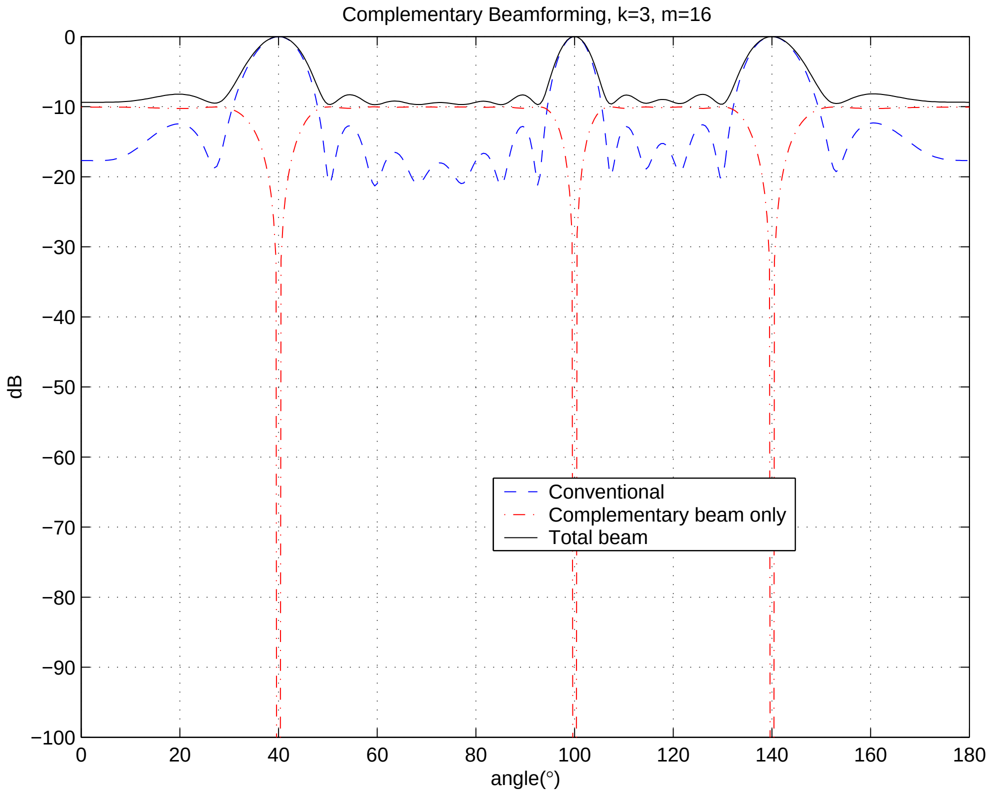
determined by a random bit stream, then for large L, we have the same effect and we can send $2p$ coded bits using U_j^H.

- Thus, we can send $2p(m-k)$ coded bits in the complementary direction.
- Other constellations apart from ± 1 can also be used as long as they are symmetric about the origin.

Sending Data Using The Complementary Beam

- Usually the bits send using complementary beam are heavily coded.
- These bits can be used to send control information.
- They may not be completely random due to presence of coding.
- This may lead to some fluctuations in the complementary beam shape.

Time Domain CBF

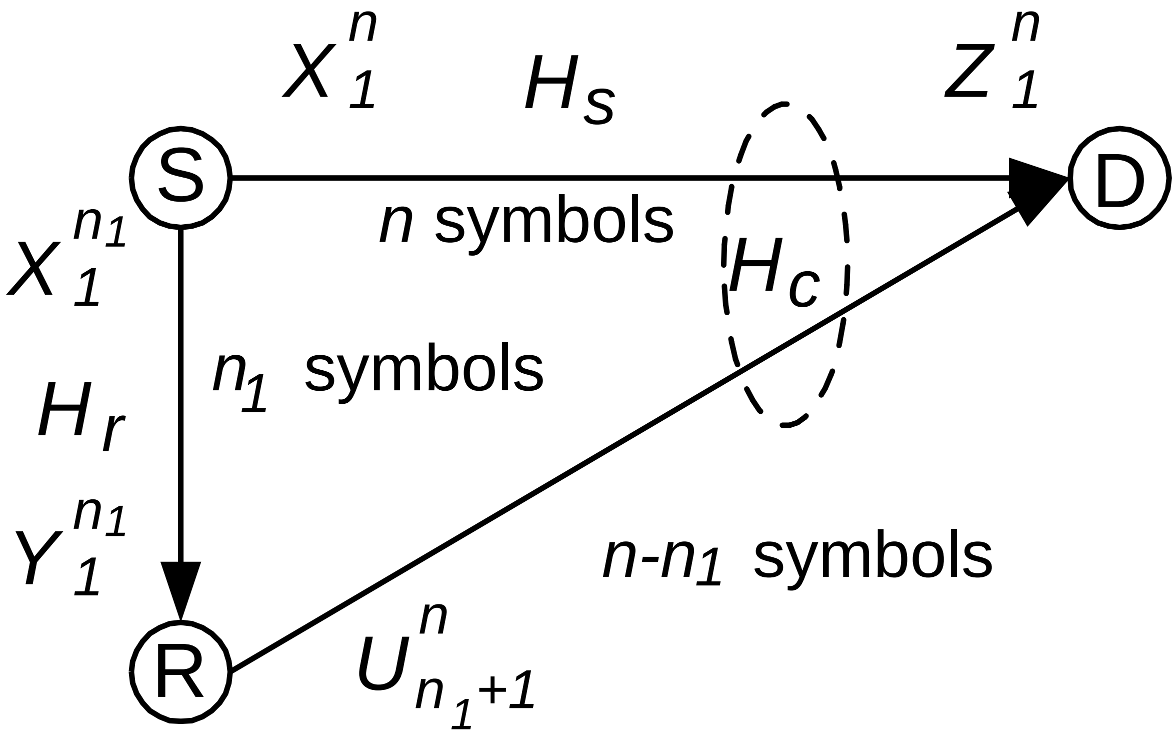


Distributed STC/BF

The Main Idea

- A source S would like to transmit data to a receiver D.
- S asks nearby transmitters to help him produce the effects of a distributed space-time code or distributed beamforming at the receiver.
- D may ask neighboring receivers to help with reception and beamforming.
- This motivates distributed space-time coding/beamforming.
- This idea has been studied also under relaying in the literature.

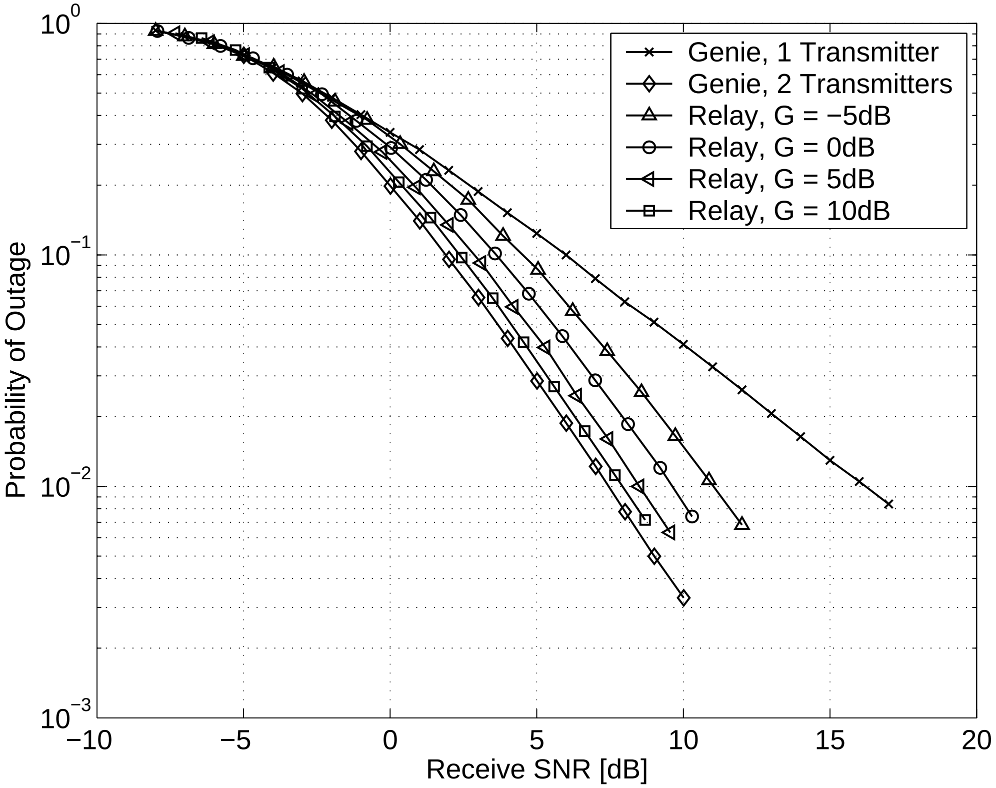
The Main Idea



Capacity

- We have studied this problem under the assumption that the Tx (resp. Rx) collaborators are closer to the Tx (resp. Rx) than the Rx (resp. Tx).
- This gives a path gain at the collaborators.
- We refer to this as the geometric gain.
- This allows for a Tx (resp. Rx) to tell the collaborators very quickly what it intends to send.
- We computed the capacity and compared it to the ideal case (MIMO capacity).

The Main Idea



Comments

- We observe that using distributed communications (in theory) with a reasonable geometric gain, the capacity of MIMO (non-distributed systems) can be achieved.
- This can potentially give substantial capacity improvements.
- However, many practical issues remain to be addressed.
- These include frequency and time synchronization, collaborative coding and decoding, distributed power control, etc.
- We are currently working on these problems and there seems to be some hope to resolve them.

Conclusions

- By employing smart antennas/MIMO techniques, the capacity and range of wireless systems can be dramatically increased.
- We reviewed space-time coding and beamforming techniques.
- Combining smart antennas and CSMA produce a host of new challenges. An example of these problems is the hidden beam problem.
- We proposed complementary beamforming to address this problem. The complementary beam can also be used to carry low data rate control information.
- We discussed distributed space-time coding/beamforming.
- Distributed space-time coding/beamforming can potentially produce the gains of MIMO communications.