Smart Antennas for Wireless Systems

Jack H. Winters

March 21, 2004

jwinters@motia.com

TABLE OF CONTENTS

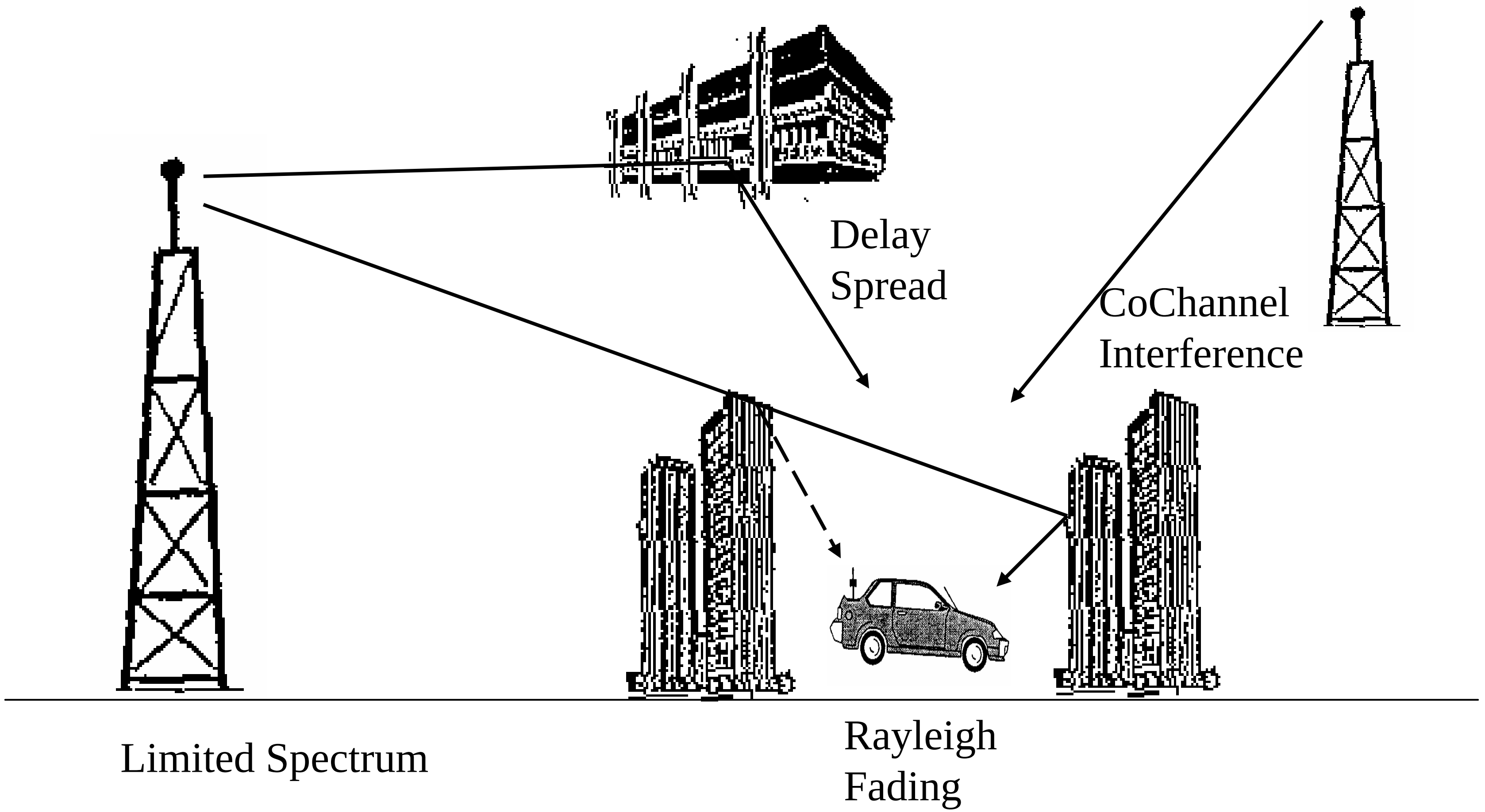
GOAL

In this tutorial, we will discuss current and future antenna technology for wireless systems and the improvement that smart and adaptive antenna arrays can provide. We will describe standard cellular antennas, smart antennas using fixed beams, and adaptive antennas for base stations, as well as antenna technologies for handsets and other wireless devices. We will show the potential improvement that these antennas can provide, including range extension, multipath diversity, interference suppression, and capacity increase.

The issues involved in incorporating these antennas into wireless systems, including 2nd generation (CDMA, GSM, and IS-136), 3rd generation (WCDMA and EDGE), and future cellular systems, as well as other wireless systems, such as wireless local area networks (WLAN's) in different environments, such as rural, suburban, and urban areas, as well as indoors, will be described in detail. Theoretical, computer simulation, experimental, and field trial results will be presented. This tutorial should provide a basic understanding of the antenna technology options and their potential in wireless systems.

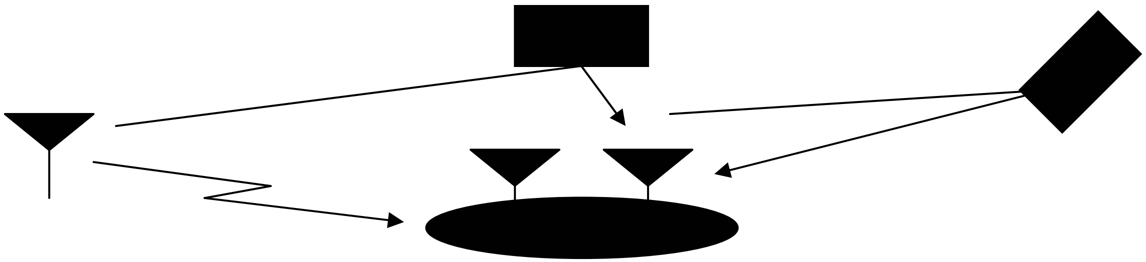
WIRELESS SYSTEM IMPAIRMENTS

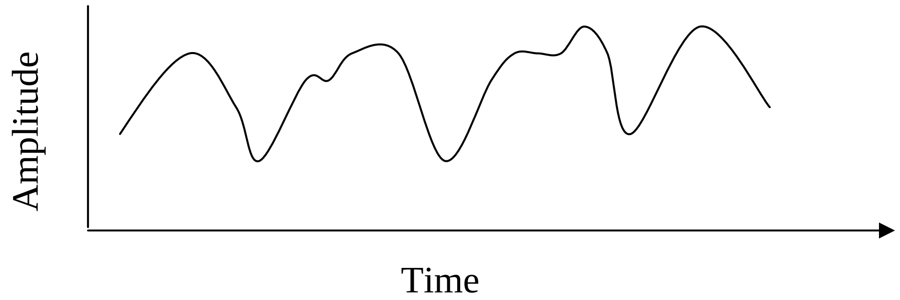
Wireless communication systems are limited in performance and capacity by:



MULTIPATH

- Many paths ⇒ Rayleigh fading (complex Gaussian channel)
- Flat fading (negligible ISI) if $\Delta\tau < 10\%$ T (symbol period)
- Fading is independent with distance ($>\lambda/4$), direction, and polarization
- Distribution of bit error rate (BER) ⇒ outage probability $P_0 = Pr(BER > BER_0)$

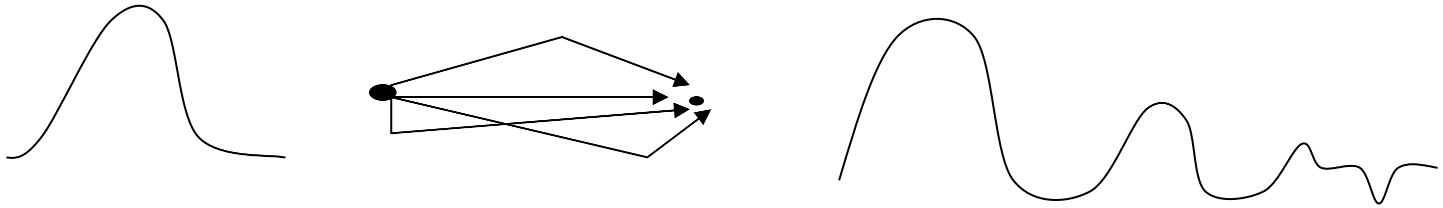




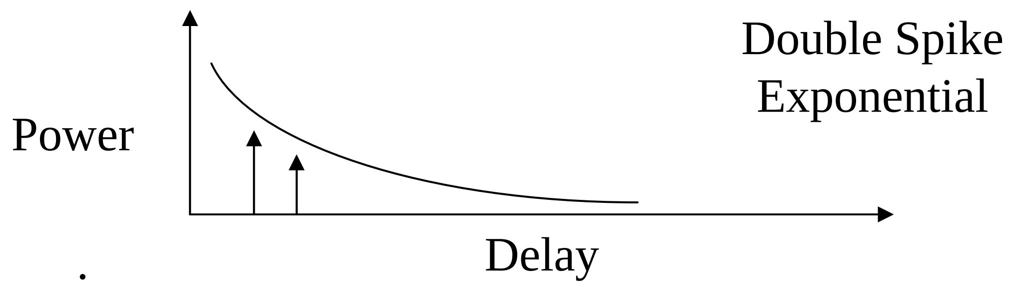
DELAY SPREAD

$\Delta\tau > 10\%T$

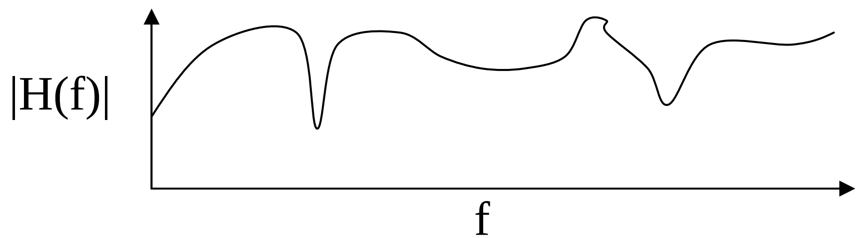
Time domain



Delay spectrum



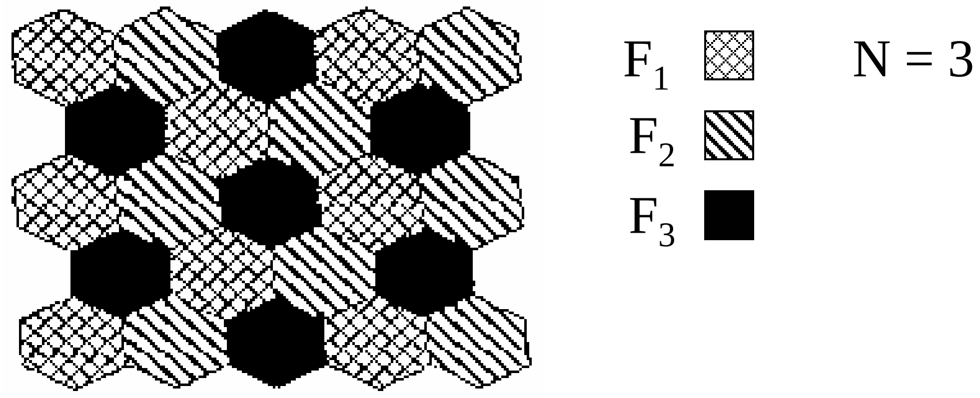
Frequency domain



Intersymbol interference (ISI)

CO-CHANNEL INTERFERENCE (CCI)

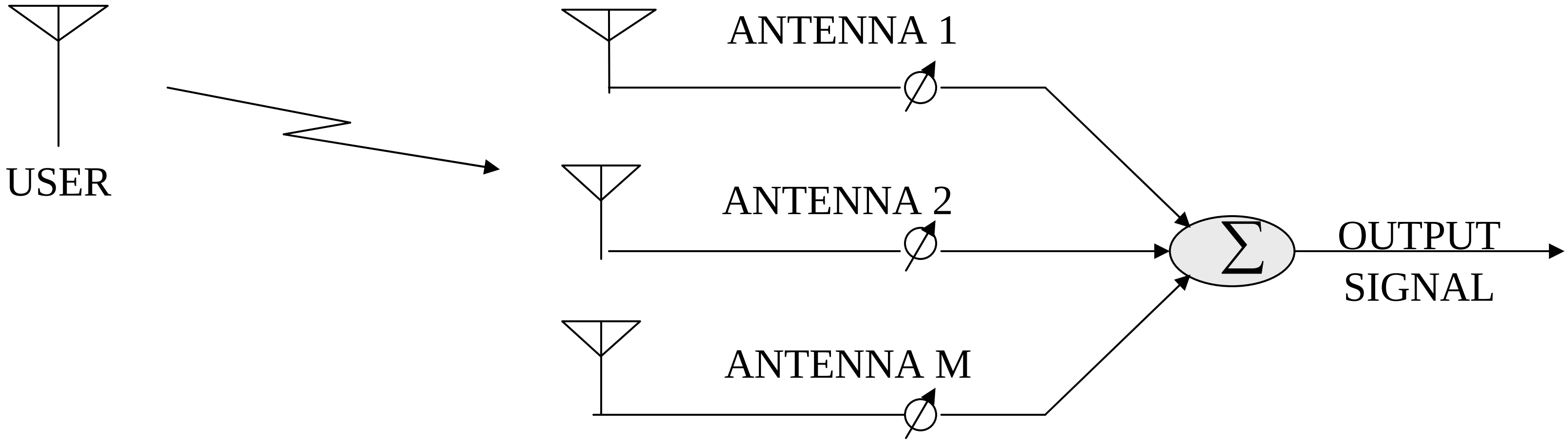
- Cellular systems use frequency reuse for capacity increase



- To increase capacity further: shrink cell size, increase reuse
- N = 7 frequency reuse currently
- Six closest interferers (S/I set by N only)
- One interferer usually dominates
- CCI assumed Gaussian noise in most studies

ANTENNA DIVERSITY

Multiple antenna elements with received signals weighted and combined



With multipath, diversity gain requires independent fading:

- $\lambda/4$ spacing
- Direction
- Polarization

ANTENNA AND DIVERSITY GAIN

Antenna Gain: Increased average output signal-to-noise ratio

- Gain of M with M antennas
- Narrower beam with $\lambda/2$-spaced antenna elements

Diversity Gain: Decreased required receive signal-to-noise ratio for a given BER averaged over fading

- Depends on BER - Gain for M=2 vs. 1:
  - 5.2 dB at 10^{-2} BER
  - 14.7 dB at 10^{-4} BER
- Decreasing gain increase with increasing M - 10^{-2} BER:
  - 5.2 dB for M=2
  - 7.6 dB for M=4
  - 9.5 dB for $M=\infty$
- Depends on fading correlation

• Antenna diversity gain may be smaller with RAKE receiver in CDMA

DIVERSITY TYPES

Spatial: Horizontal separation

- Correlation depends on angular spread

Polarization: Dual polarization

- Low correlation
- Horizontal receive 6-10 dB lower than vertical with vertical transmit and LOS

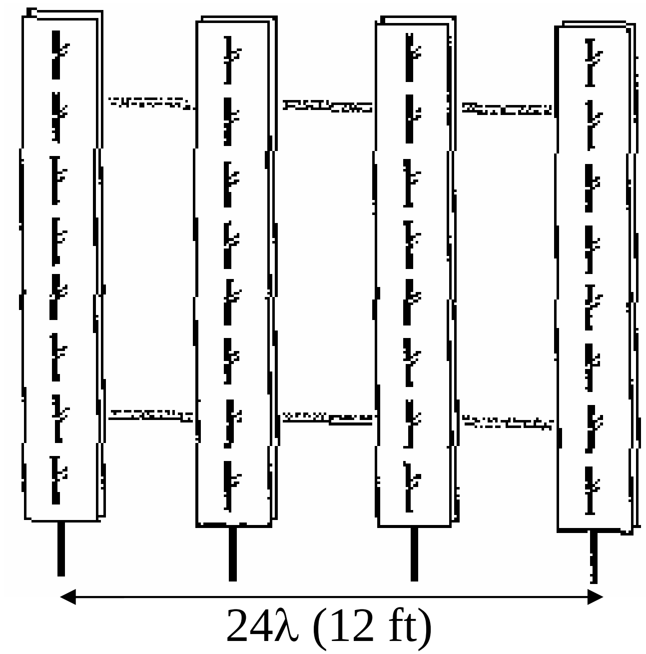
Angle: Adjacent narrow beams

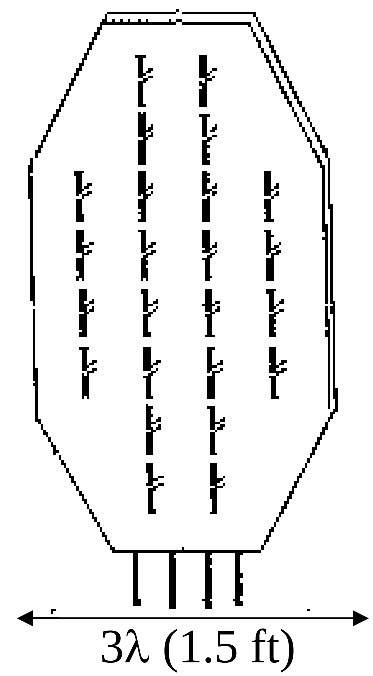
- Low correlation typical
- 10 dB lower signal in weaker beam, with small angular spread

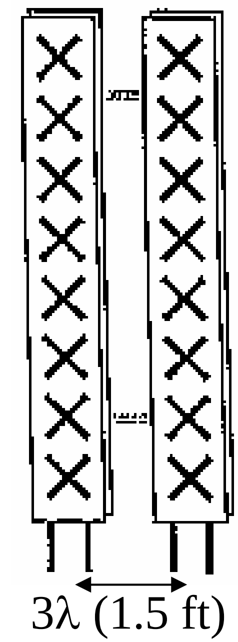
ADAPTIVE ARRAYS FOR TDMA BASE STATIONS

AT&T Wireless Services and Research - Field Trial with Lucent

7/96-10/96







Field trial results for 4 receive antennas on the uplink:

• Range extension: 40% reduction in the number of base stations can be obtained 4 to 5 dB greater margin $\Rightarrow$ 30% greater range

• Interference suppression: potential to more than double capacity

Operation with S/I close to 0 dB at high speeds $\Rightarrow$ greater capacity and quality

DIVERSITY TYPES (wireless devices)

Spatial: Separation – only ¼ wavelength needed at terminal (10 wavelengths on basestation)

Polarization: Dual polarization (doubles number of antennas in one location

Angle: Adjacent narrow beams with switched beam antenna

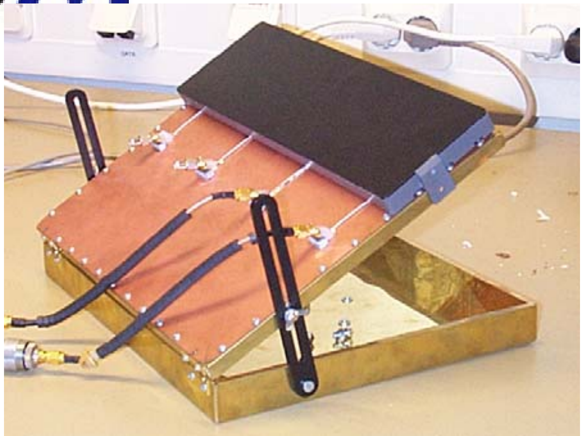
Pattern: Allows even closer than ¼ wavelength

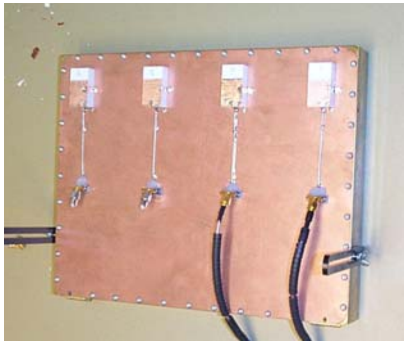
$\Rightarrow$ 4 or more antennas on a PCMCIA card

$\Rightarrow$ 16 on a handset

$\Rightarrow$ Even more on a laptop

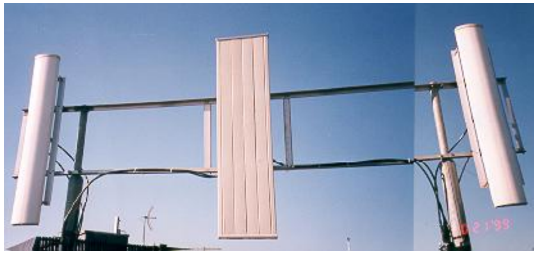
Diversity Antennas





Laptop Prototype

- **4 patch antennas at 1900 MHz separated by 3 inches (λ/2 wavelengths)**
- **Laptop prototype made of brass with adjustable PCB lid**

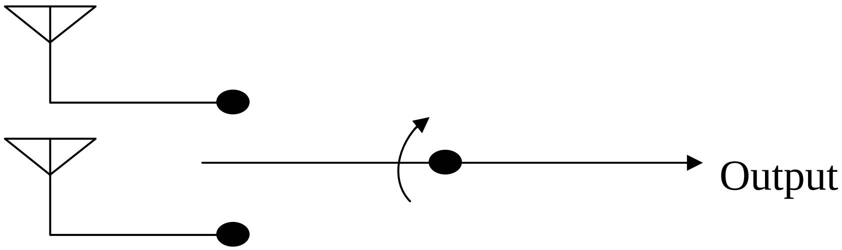


Base Station Antennas

- **Antennas mounted on 60 foot tower on 5 story office building**
- **Dual-polarized slant 45° 1900 MHz sector antennas and fixed multibeam antenna with 4 - 30° beams**

COMBINING TECHNIQUES

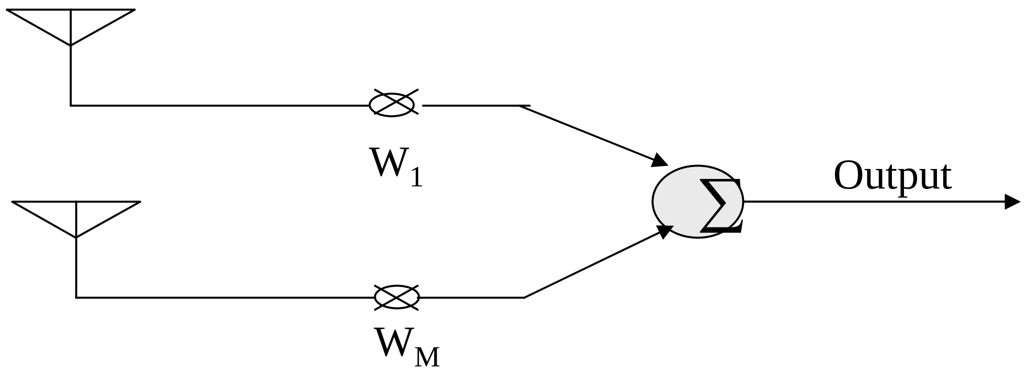
Selection:



- Select antenna with the highest received signal power
- $P_{0M} = P_0^M$

COMBINING TECHNIQUES (CONT.)

Maximal ratio combining:



• Weight and combine signals to maximize signal-to-noise ratio (Weights are complex conjugate of the channel transfer characteristic)

• Optimum technique with noise only

• $\mathrm{BER}_M \approx \mathrm{BER}^M$ (M-fold diversity gain)

OPTIMUM COMBINING (ADAPTIVE ANTENNAS)

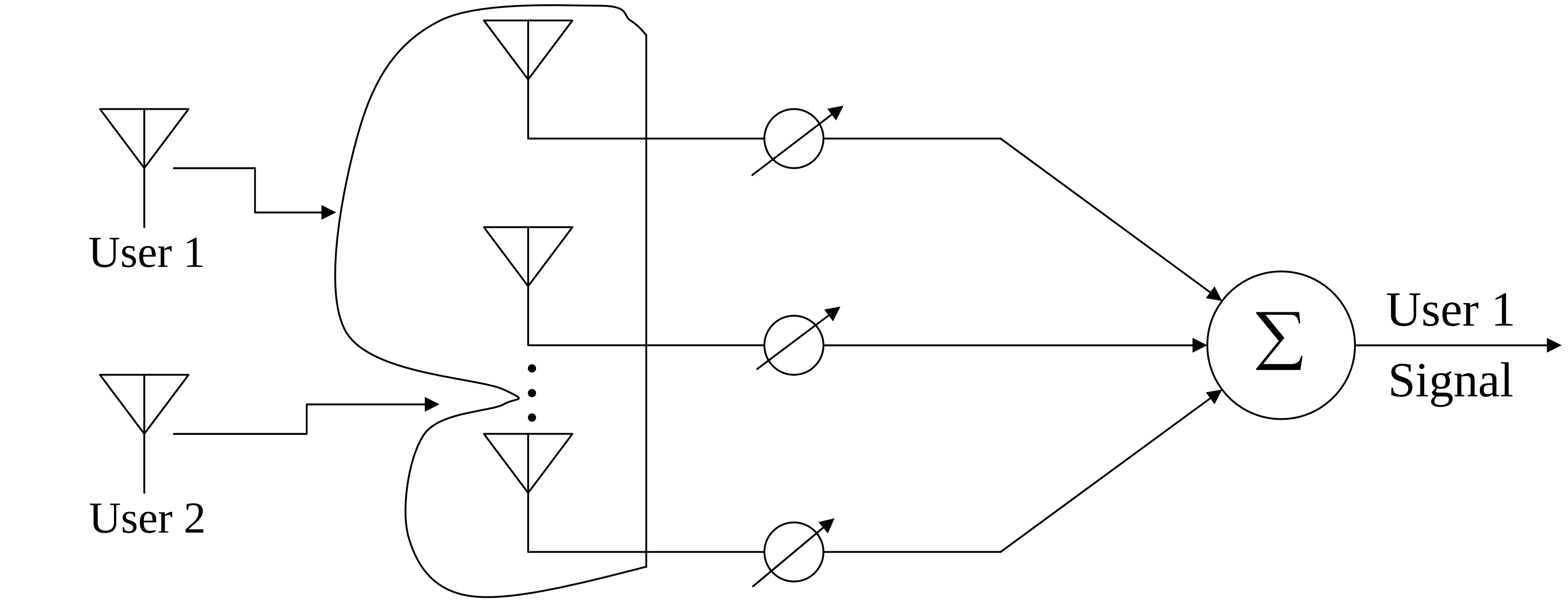
• Weight and combine signals to maximize signal-to-interference-plus-noise ratio (SINR)

- Usually minimize mean squared error (MMSE)

• Utilizes correlation of interference at the antennas to reduce interference power

• Same as maximal ratio combining when interference is not present

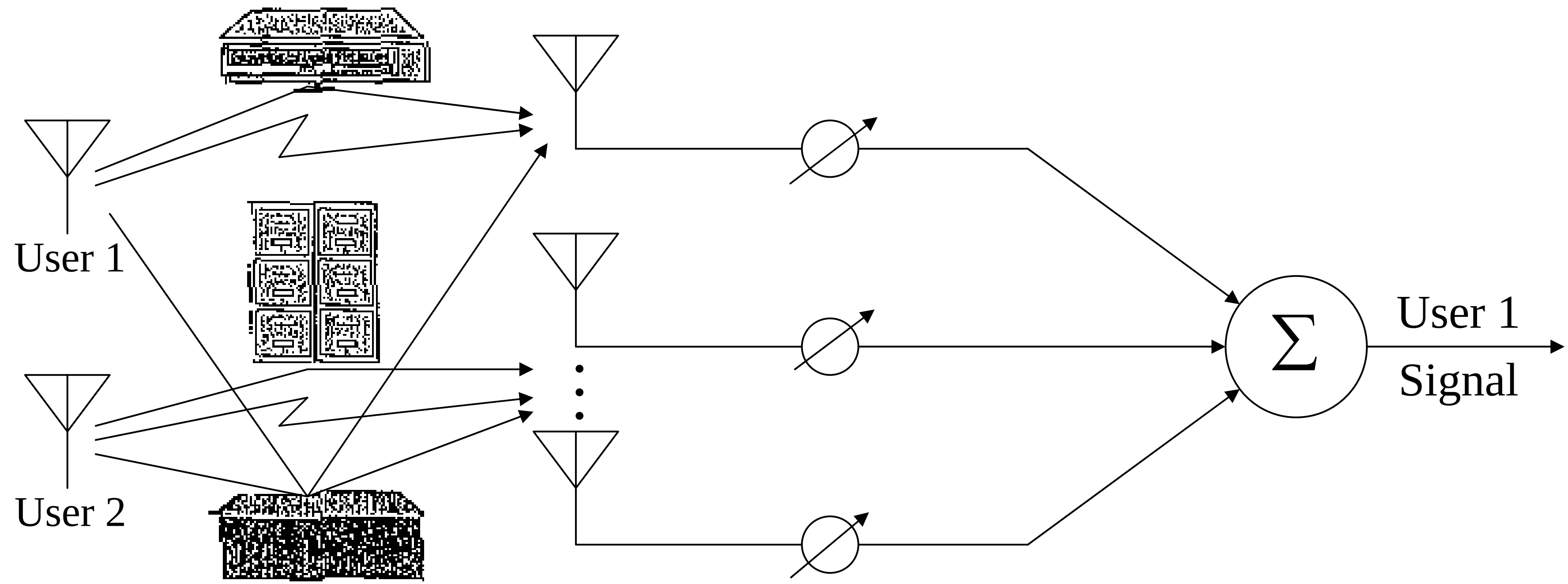
INTERFERENCE NULLING
Line-Of-Sight Systems



Utilizes spatial dimension of radio environment to:

- Maximize signal-to-interference-plus-noise ratio
- Increase gain towards desired signal
- Null interference: M-1 interferers with M antennas

INTERFERENCE NULLING
Multipath Systems

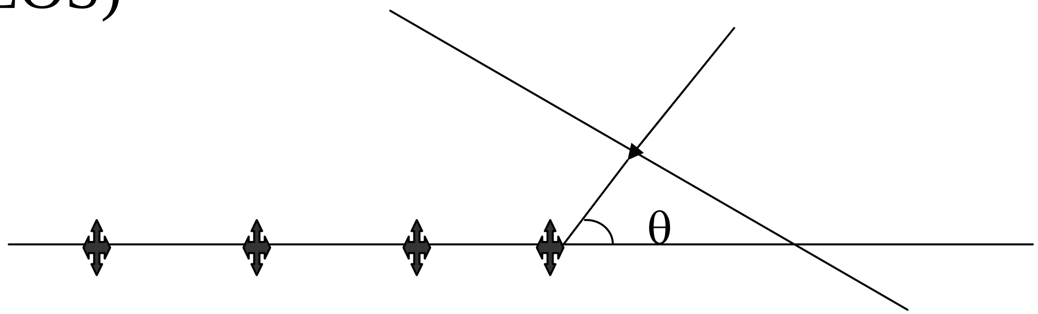


Antenna pattern is meaningless, but performance is based on the number of signals, not number of paths (without delay spread).

=> A receiver using adaptive array combining with M antennas and N-1 interferers can have the same performance as a receiver with M-N+1 antennas and no interference, i.e., can null N-1 interferers with M-N+1 diversity improvement (N-fold capacity increase).

SPATIAL VS. ANGULAR DOMAIN

- Number of rays < number of antennas ⇒ angular domain (LOS)

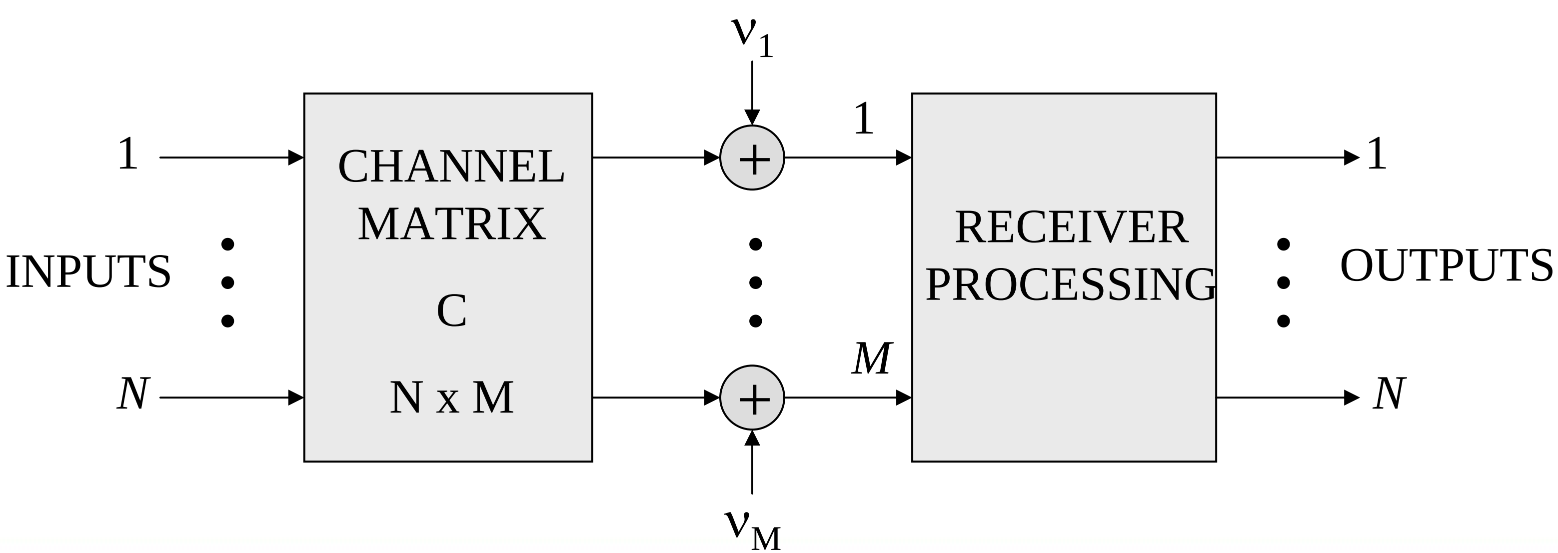


- Number of rays > number of antennas ⇒ spatial domain (multipath)

THEORY

Model:

- N transmitters, 1 to N outputs
- At each output, 1 desired signal and N-1 interferers
- M receiving antennas, with channel matrix C=[C_{ij}], where C_{ij} is the channel coefficient between transmitter i and antenna j



THEORY (CONT'D)

Assumptions:

- Flat Rayleigh fading
- Antennas spaced far enough for independent fading

  - $C_i = [C_{i1}\ \Lambda\ C_{iM}]$ are linearly independent
  - C_{ij} are complex i.i.d. zero-mean Gaussian random variables

- Noise is additive, zero-mean i.i.d. Gaussian

Goal: Linear receiver cancels *N*-1 interferers and maximizes desired signal SNR

THEORY (CONT'D)

Solution for $N = 1$ (no interferers):

- $W = C_1^*$

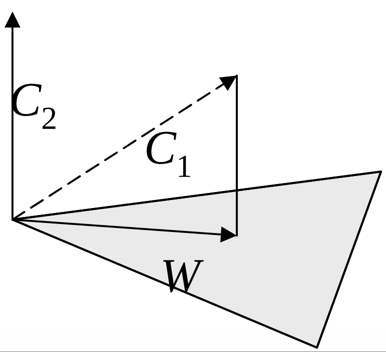
- $P_e \le E_C \exp\left\{-\rho \sum_{j=1}^{M} \left|C_{1j}\right|^2\right\} = (1+\rho)^{-M}$

- Maximal ratio combining

THEORY (CONT'D)

Solution for $N \geq 2$ (N-1 interferers):

- To cancel interferers W must be orthogonal to $C_2 \Lambda C_N$
- W is the projection of C_1^* onto the M-N+1 dimensional space orthogonal to $C_2 \Lambda C_N$
- Since the elements of C_1^* are i.i.d. Gaussian random variables, W has M-N +1 dimensions, with the same statistics as C_1, independent of $C_2 \Lambda C_N$
- $$P_e \leq E_z \exp\left\{-\rho \sum_{i=1}^{M-N+1} \left|Z_i\right|^2\right\} = (1+\rho)^{-(M-N+1)}$$



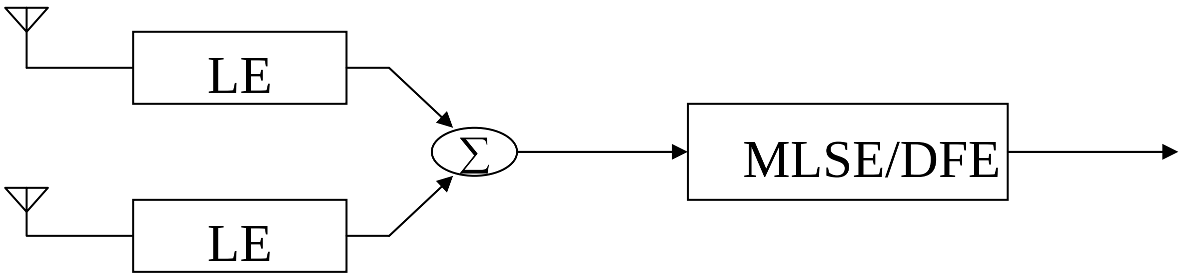
RESULT

A receiver using linear (optimum) combining with M antennas and N-1 interferers has the same performance as a receiver with M-N+1 antennas and no interference

• Null N-1 interferers with M-N+1 diversity improvement (N-fold capacity increase)

EQUALIZATION

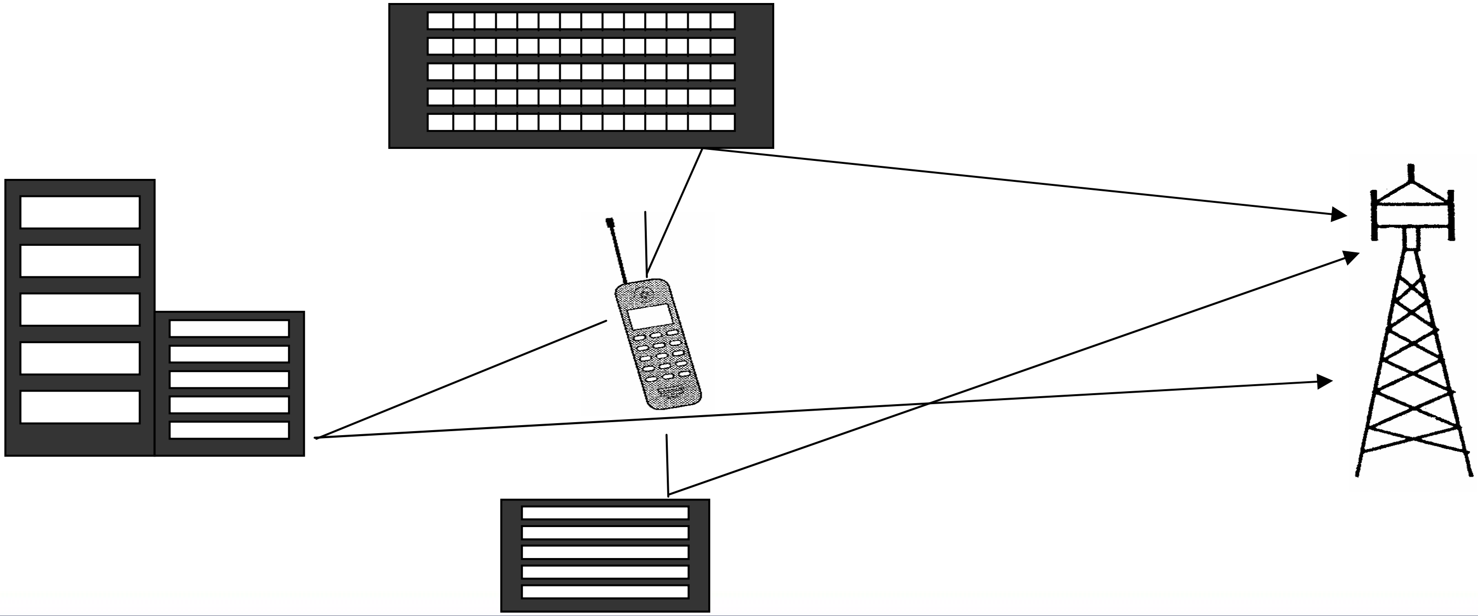
- Delay spread: Delay spread over $[(M\text{-}1) / 2]T$ or M-1 delayed signals (over any delay) can be eliminated
- Typically use temporal processing with spatial processing for equalization:



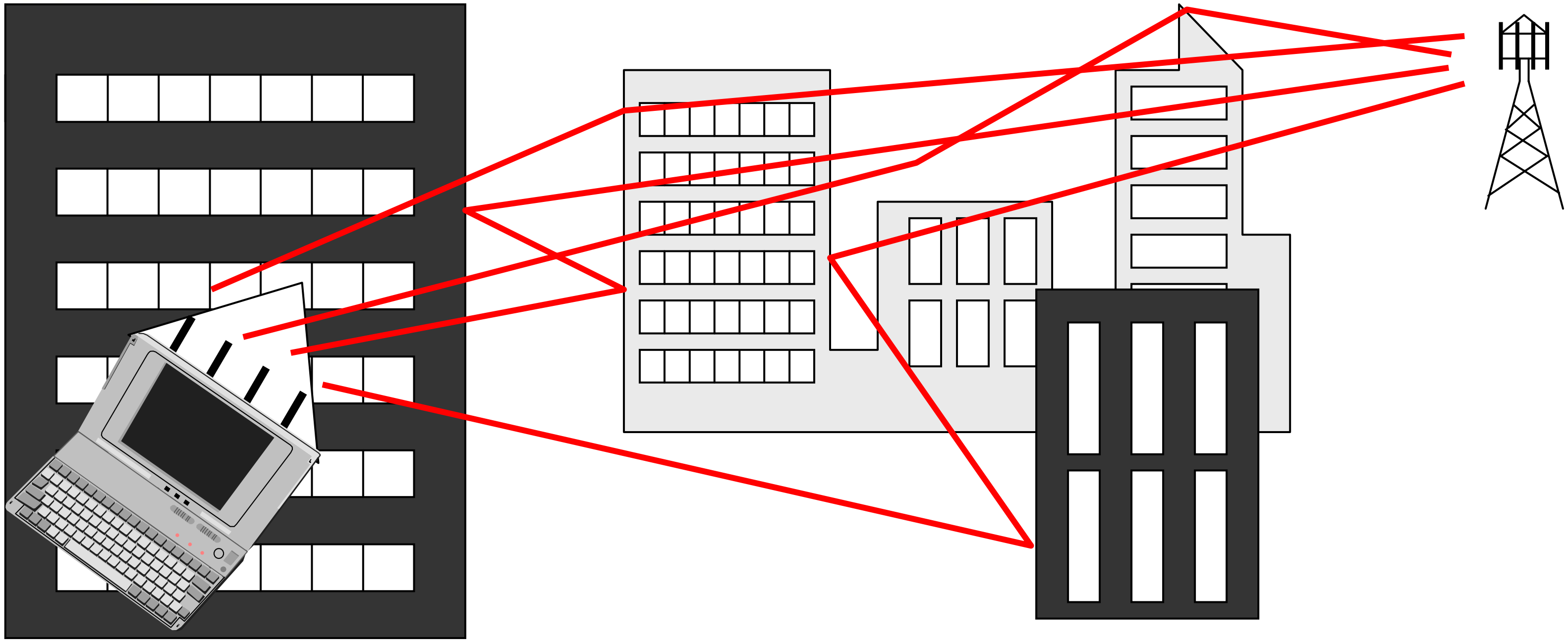
- Spatial processing followed by temporal processing has degradation, but this degradation can be small in many cases

MIMO CAPACITY INCREASE

- With *M* antennas at both the base station and mobiles, *M* independent channels can be provided in the same bandwidth if the multipath environment is rich enough.
  - 1.2 Mbps in a 30 kHz bandwidth using 8 transmit and 12 receive antennas demonstrated by Lucent (indoors).
  - Separation of signals from two closely-spaced antennas 5 miles from the base station demonstrated by AT&T/Lucent.



Multiple-Input Multiple-Output (MIMO) Radio



- With M transmit and M receive antennas, can provide M independent channels, to increase data rate M-fold with no increase in total transmit power (with sufficient multipath) – only an increase in DSP
  - Indoors – up to 150-fold increase in theory
  - Outdoors – 8-12-fold increase typical
- Measurements (e.g., AT&T) show 4x data rate & capacity increase in all mobile & indoor/outdoor environments (4 Tx and 4 Rx antennas)
  - 216 Mbps 802.11a (4X 54 Mbps)
  - 1.5 Mbps EDGE
  - 19 Mbps WCDMA

THEORETICAL (ZERO-FORCING) RESULT

- A receiver using linear (optimum) combining with M antennas and N-1 interferers has the same performance as a receiver with M-N+1 antennas and no interference
- Multipath: M-fold diversity gain
- CCI only: N interferers eliminated (M-fold capacity increase
- Delay spread: Delay spread over $[(M-1) / 2]T$ or M-1 delayed signals (over any delay) eliminated
- CCI and multipath: N interferers eliminated with M-N-fold diversity gain
- CCI, delay spread, and multipath: N interferers with delay spread over D symbols with $M+1-(N+1)(2D+1)$-fold diversity gain

OPTIMUM COMBINING - MMSE RESULT

Practical systems (typically):

• # interferers >> M

• D >> (M-1)/2

But:

• Only need to suppress interference (and ISI) into the noise (not eliminate)

• Usually only 1 or 2 dominant interferers and delayed paths

Result:

• Substantial increase in performance and capacity even with a few (even 2) antennas

Note:

• Optimum combining yields interference suppression under all conditions (e.g., line-of-sight, Rician fading)

EXAMPLE - MULTIPATH AND CCI WITH 2 ANTENNAS

Theory (zero-forcing):

• Dual diversity against multipath (maximal ratio combining)

or

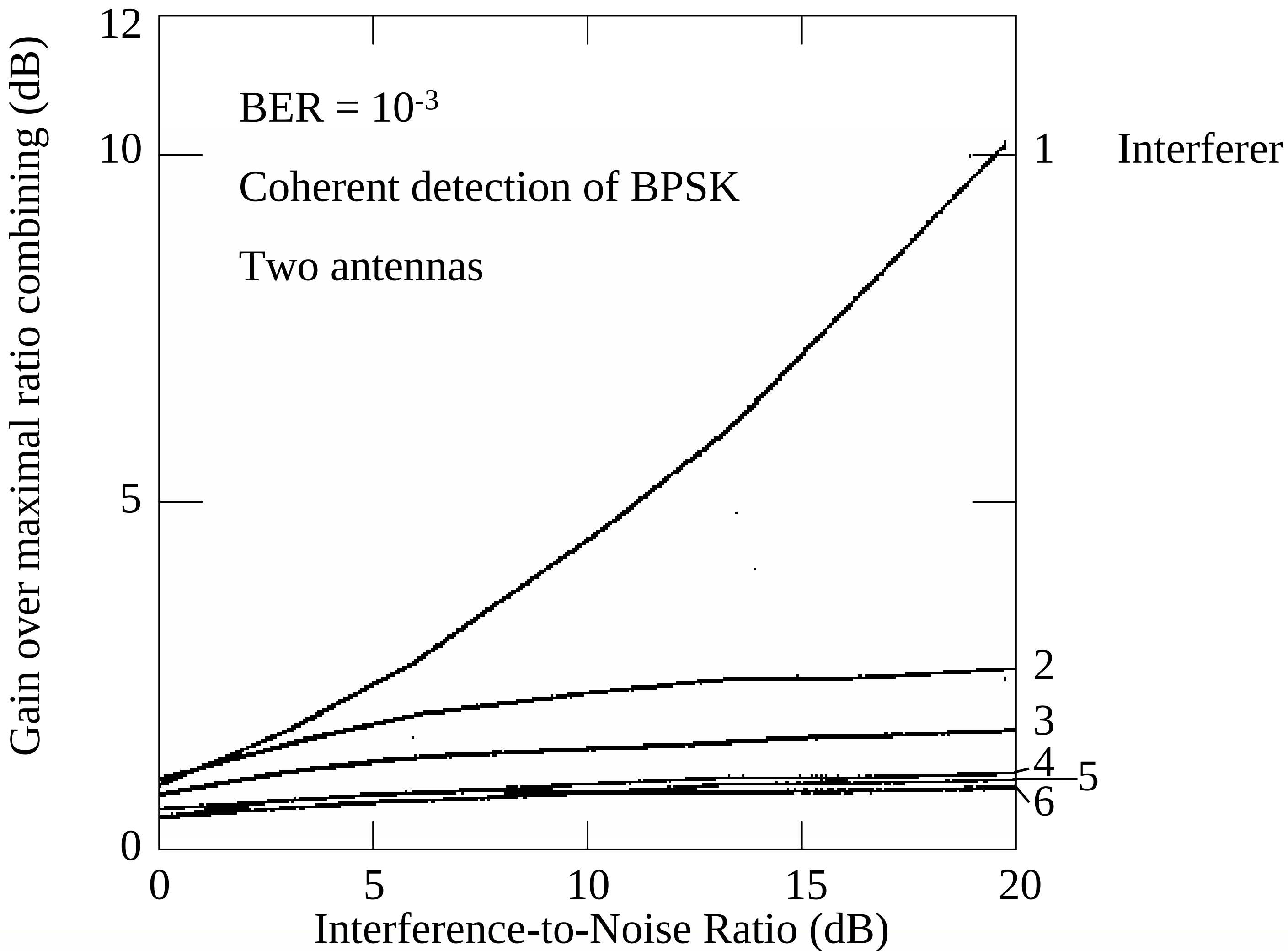
• Elimination of one interferer (gain = INR - 12.8 dB) without diversity gain {INR - interference to noise ratio, BER = 10^{-3}}

MMSE result:

• Gain over maximal ratio combining ≈ INR/2 (in dB) with one interferer

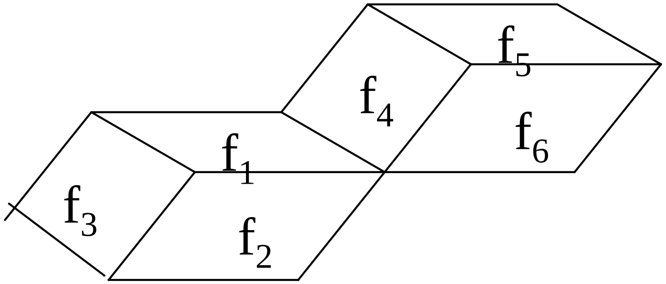
• Gain of 1 to 2 dB with 2 to 6 equal-strength interferers

EXAMPLE - MULTIPATH AND CCI WITH ADAPTIVE ANTENNAS



SMART ANTENNAS

Today: Cellular systems with sectorization (120°) $\Rightarrow$ handoffs between sectors

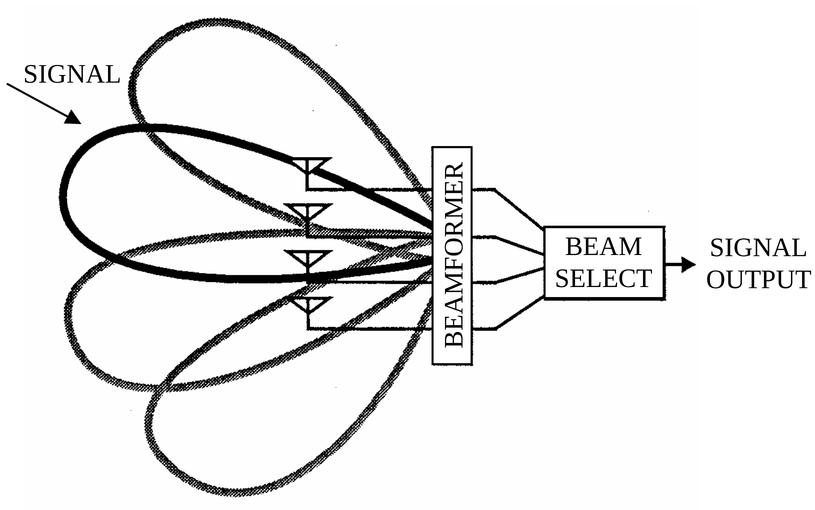


For higher performance $\Rightarrow$ Narrower sectors $\Rightarrow$ Too many handoffs

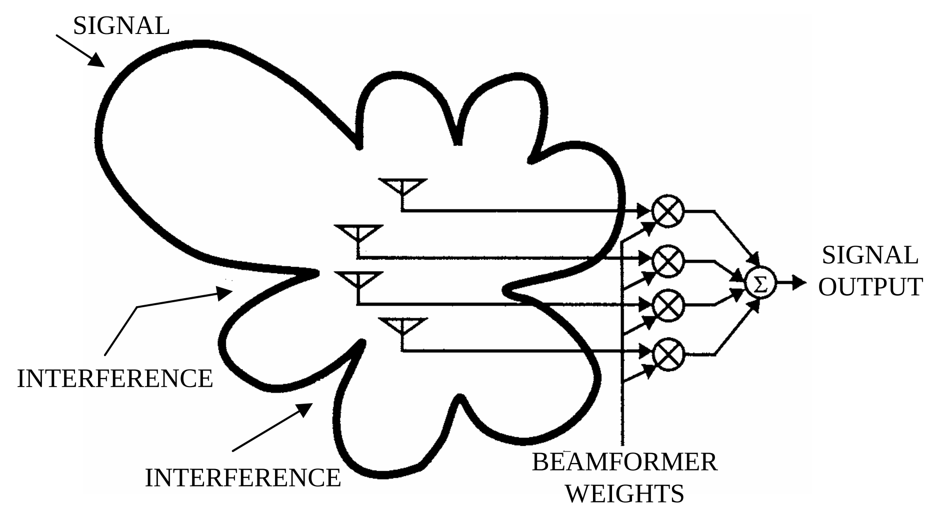
Smart Antenna: Multibeam antenna or adaptive array without handoffs between beams

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array



Smart antenna is a multibeam or adaptive antenna array that tracks the wireless environment to significantly improve the performance of wireless systems

Adaptive arrays in any environment provide:

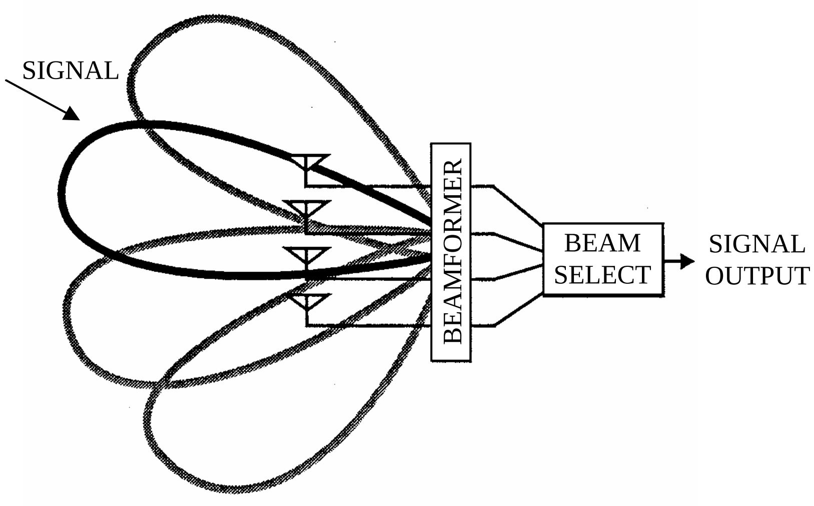
- Antenna gain of M
- Suppression of M-1 interferers

In a multipath environment, they also provide:

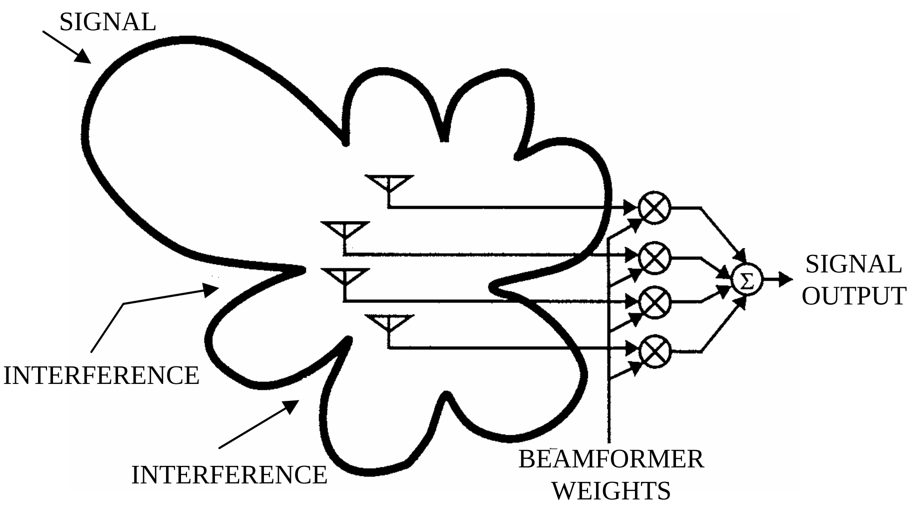
- M-fold multipath diversity gain
- With M Tx antennas (MIMO), M-fold data rate increase in same channel with same total transmit power

Smart Antennas

Switched Multibeam Antenna



Adaptive Antenna Array



Smart Antennas can significantly improve the performance of wireless systems

- Higher antenna gain / diversity gain ⇒ Range extension and multipath mitigation
- Interference suppression ⇒ Quality and capacity improvement
- Suppression of delayed signals ⇒ Equalization of ISI for higher data rates
- Multiple signals in the same bandwidth ⇒ Higher data rates

Switched Multibeam versus Adaptive Array Antenna: Simple beam tracking, but limited interference suppression and diversity gain

SMART/ADAPTIVE ANTENNA ARRAY TECHNOLOGY

Motia

Military

- high resolution direction-finding
- jammer cancellation
- interference reduction
- signal classification
- directional transmission
- custom VLSI implementations

Commercial

- mobile, indoor, wireless local loop
- range extension
- interference reduction with fast fading
- signal acquisition and tracking
- delay spread equalization
- propagation characterization
- adaptive retransmission
- antenna design and implementations

Research

Applications

1980

- long range surveillance radars
- military communication systems
- sonar
- geophysical exploration
- imaging

1990

- Nortel SmartBTS - GSM
- MetaWave SpotLight
- ArrayComm IntelliCell
- Celwave Smart System - AMPS
- Hazeltine IAS - AMPS
- Ericsson and Lucent - IS-136

2000

- 3G
- WLAN
- WiMAX
- UWB
- 802.20
- Satellite radio/TV

CELLULAR APPLICATIONS

IS-136

GSM

EDGE

CDMA

- Range increase (2 GHz versus 900 MHz $\Rightarrow$ 9 dB)
- Capacity increase (higher reuse)
- Data rate increase (wireless Internet access)

IS-136

- TDMA with 3 users per channel
- $\pi/4$ DQPSK at 48.6 kbps
- 162 symbols/slot
- 14 symbol synchronization sequence
- Two receive antennas at base (Tracking over slot, but spatial processing before equalization is adequate)

IS-136 Timing Structure

Digital Traffic Channel

TDMA FRAME 40 ms

1	2	3	4	5	6

TIME SLOT 6.687 ms (162 symbols)

3	3	8	14	61	6	6	61
G	R	DATA	SYNC	DATA	SACCH	CDVCC	DATA

MOBILE TO BASE

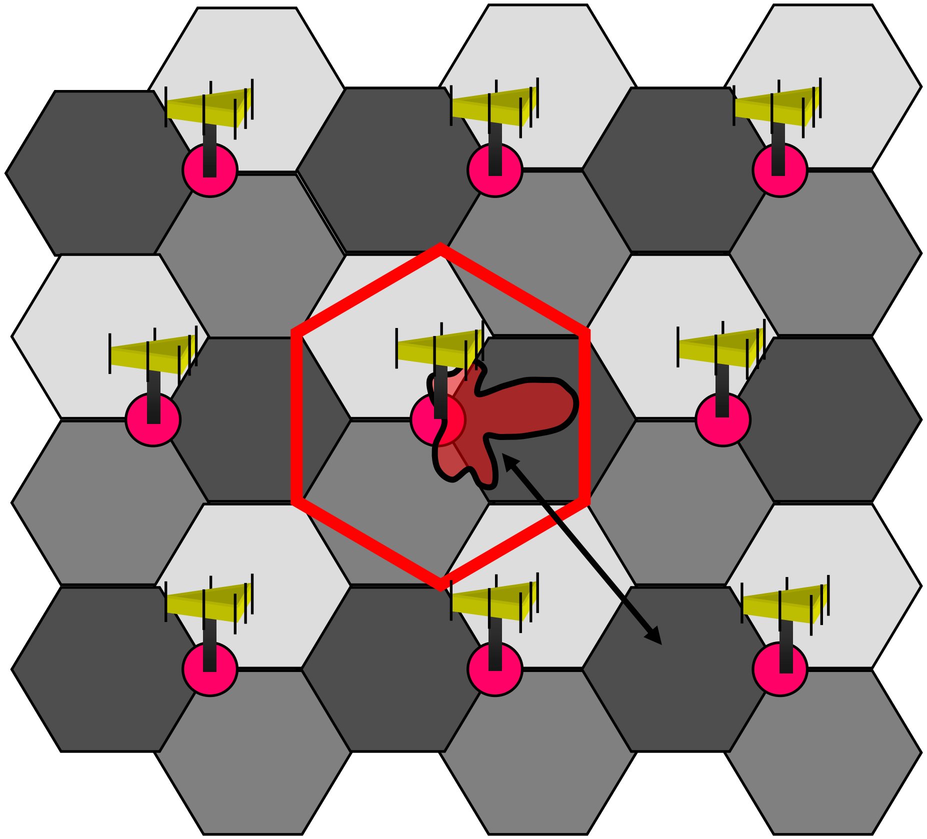
14	6	65	6	65	1	5.5
SYNC	SACCH	DATA	CDVCC	DATA	RSVD	CDL

BASE TO MOBILE

Symbol duration 41 µs (48.6 kb/s)

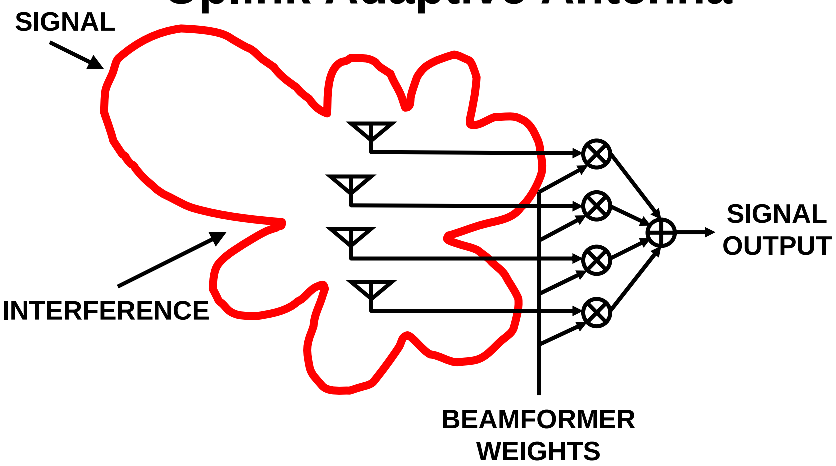
Smart Antennas for IS-136

- Key enhancement technique to increase system capacity, extend coverage, and improve user experience in cellular (IS-136)

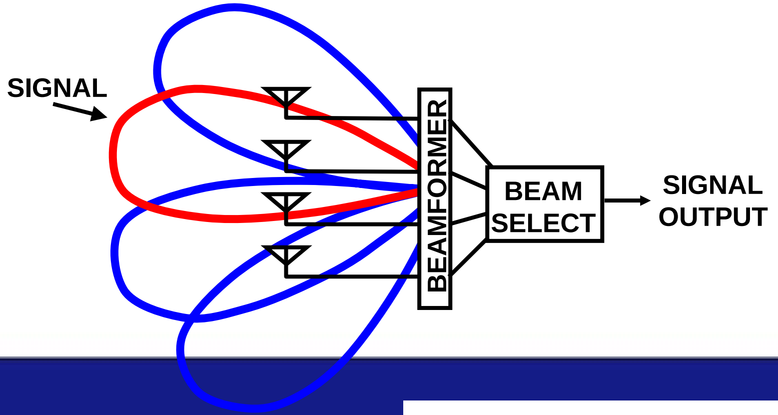


In 1999, combining at TDMA base stations changed from MRC to MMSE for capacity increase

Uplink Adaptive Antenna

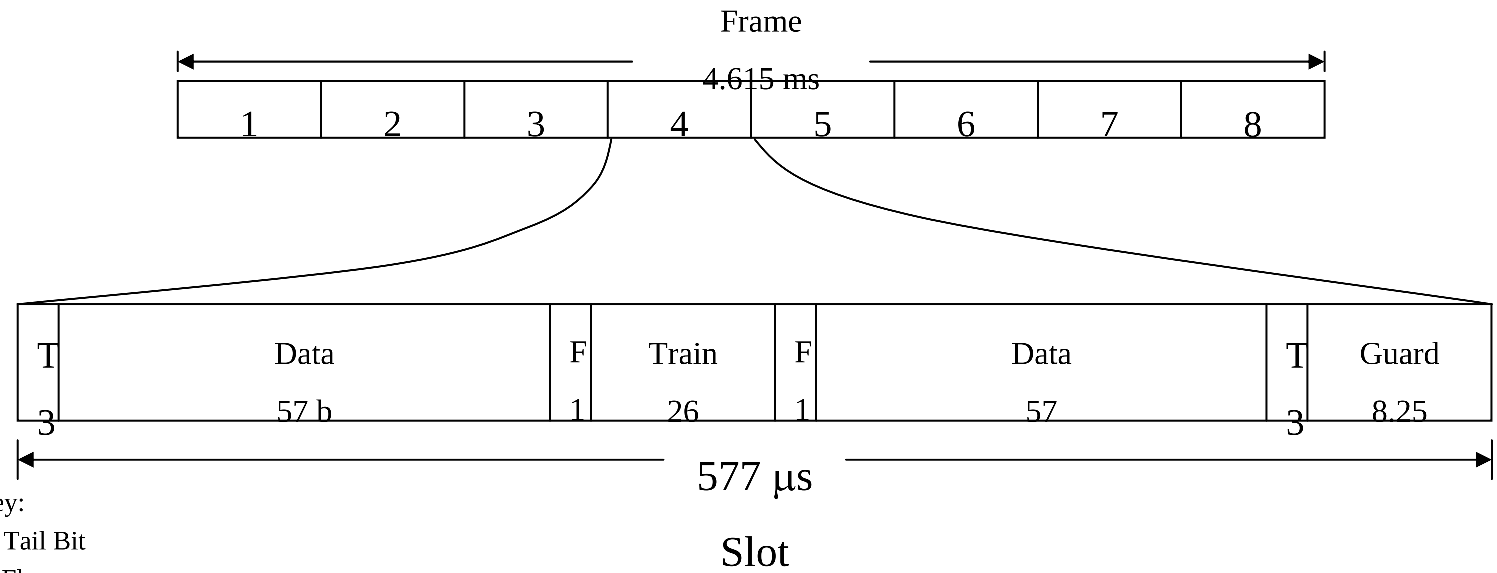


Downlink Switched Beam Antenna



GSM

- TDMA with 8 users per channel
- Gaussian MSK at 270.833 kbps
- 156.25 bits/slot
- 26 bit synchronization sequence
- Two receive antennas at base (weights fixed over slot, but S-T processing is needed)

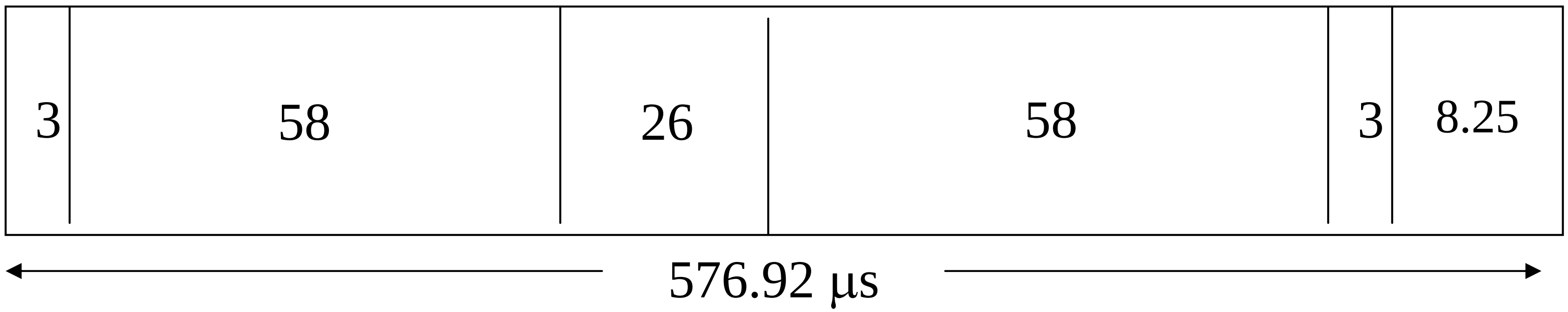


Key:
T: Tail Bit
F: Flag
Train: Equalizer Training Sequence

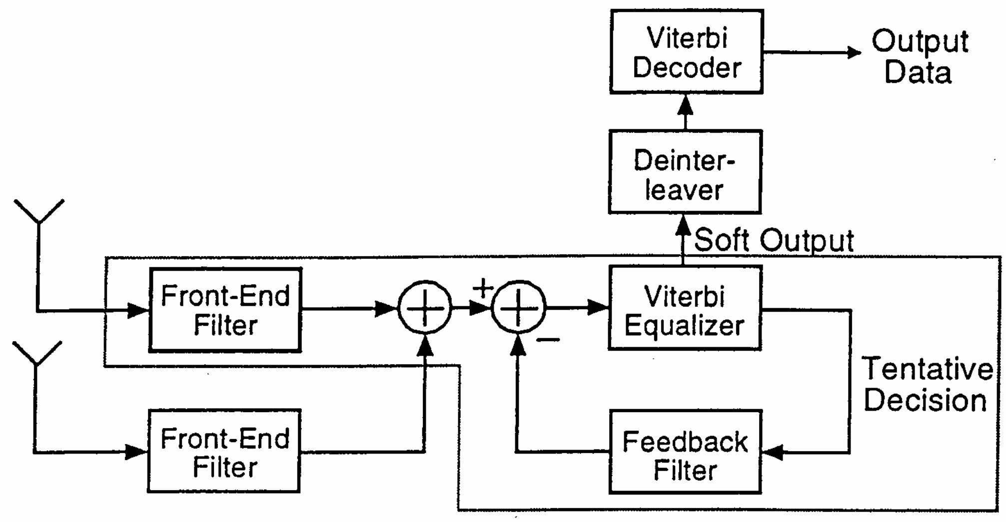
SMART ANTENNAS IN THIRD GENERATION SYSTEMS: EDGE

Motia

- High data rate (384 kbps) service based on GSM, for both Europe and North America
- 8PSK at 270.833 ksps
- 26 symbol training sequence
- 1/3, 3/9 or 4/12 reuse



Spatial-Temporal processing using DDFSE for interference suppression



DDFSE

Issues: tracking, dual antenna terminals

CDMA

IS-95 (2G)

- 1.25 MHz channel
- 9.6 (13) kbps per user
- Spreading gain = 128
- Two receive antennas at base with RAKE receiver
- Common downlink pilot - Multibeam downlink difficult
- M-fold increase in gain/capacity with M-beam antenna
- Many interferers - Limited additional gain with adaptive arrays

WCDMA (3G)

- 5 MHZ channels at 4.096 Mchips/sec
- FDD & TDD duplexing
- Coherent pilot detection
- Pilot signal per user - Smart antenna downlink
- Pilot channel available on uplink
- Multirate traffic => Adaptive array can be useful
- Large numbers of interferers on uplink (but could have near-far problem, nonuniform traffic or user distribution)
- A few interferers on downlink (other base stations) => interference suppression at mobile may be useful

WCDMA with Adaptive Antennas

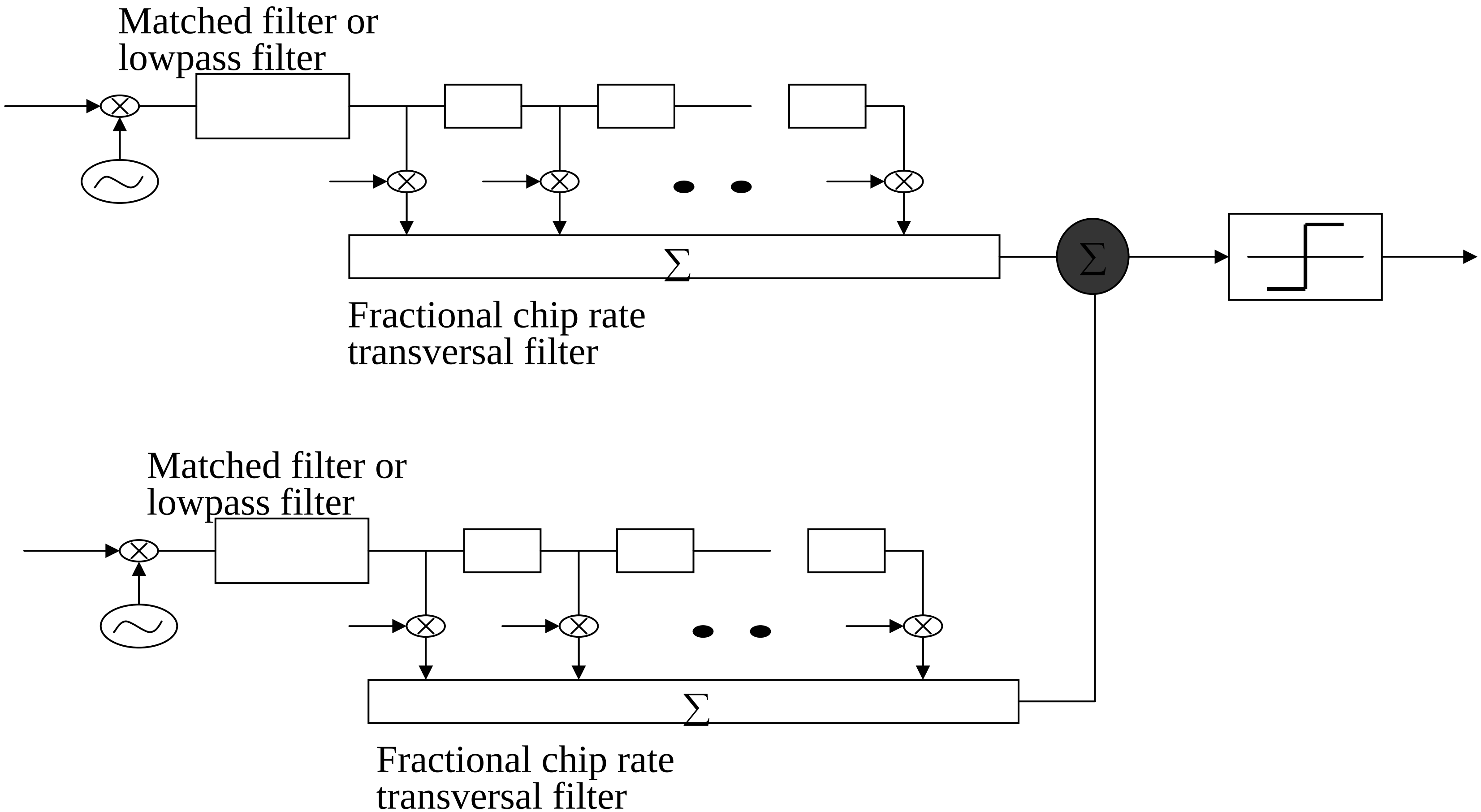
- **Techniques**
  - **S-T MMSE**
  - **S-T RAKE**
  - **Beamforming**

Space-Time MMSE

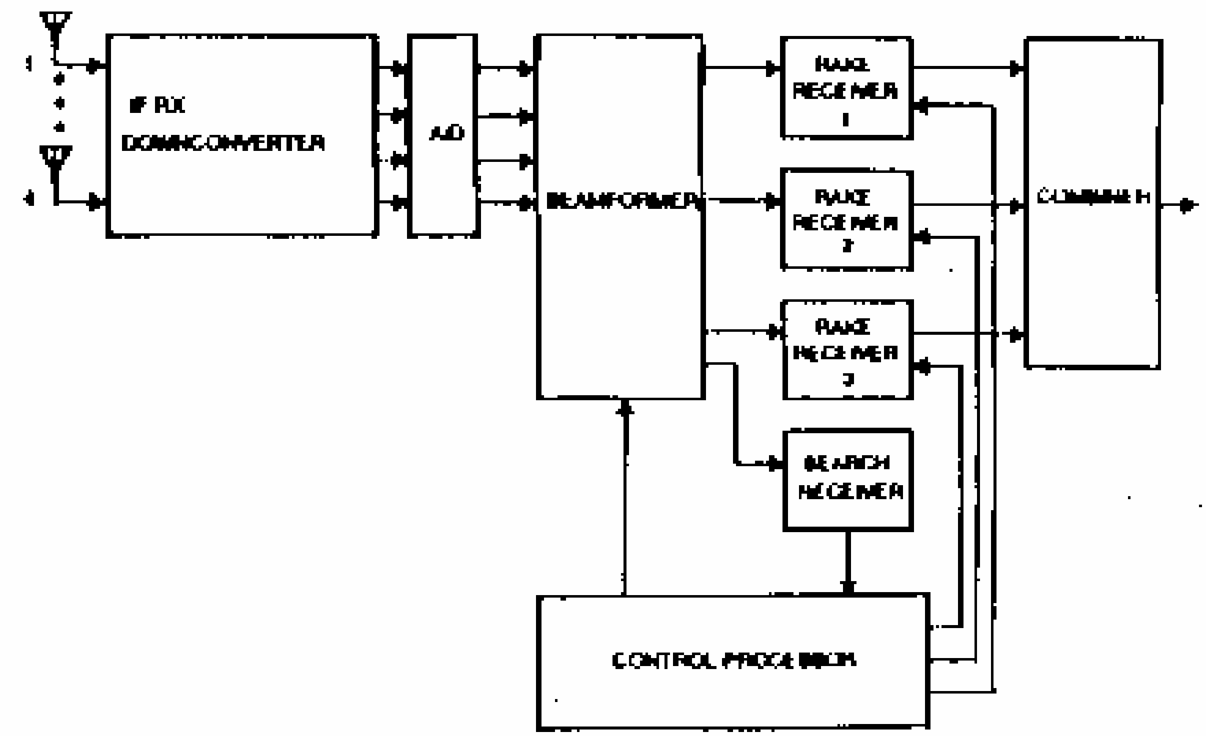
- Utilizes knowledge of desired signal and interference covariance
- Selects L out of N available fingers, with received signals combined for each finger and then finger output combined, to minimize MSE (maximize SINR)

S-T MMSE

- RAKE receiver - resolves multipath at chip duration



Space-Time RAKE



Selects L out of N available fingers, based on largest SNR (SINR) after the received signals are combined, and then output signals combined to maximize SNR or SINR

Beamforming with RAKE

- Closely-spaced antennas
- Adaptive beamforming based on
  - Nonuniform traffic
    - Adaptive sectorization
  - Few high data rate users (many voice users)
    - Null steering
- Can be used on uplink *and* downlink

RANGE INCREASE

- Fixed beam versus adaptive array
- TDMA versus CDMA

PHASED ARRAYS

• Fixed (or steerable) beams

• Consider cylindrical array with M elements ($\lambda/2$ spacing)

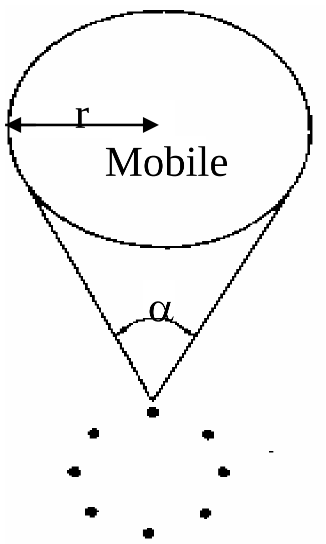
- Diameter $\approx$ (M / 4π) feet at 2 GHz

•With small scattering angle ($\gamma = 4$):

- Margin = $10\log_{10}M$ (dB)

- Number of base stations = $M^{-1/2}$

- Range = $M^{1/4}$

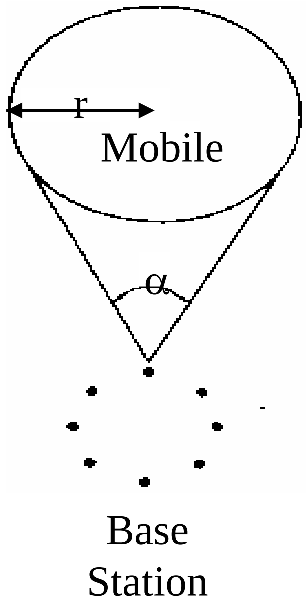


• Disadvantages:

- No diversity gain (unless use separate antenna)

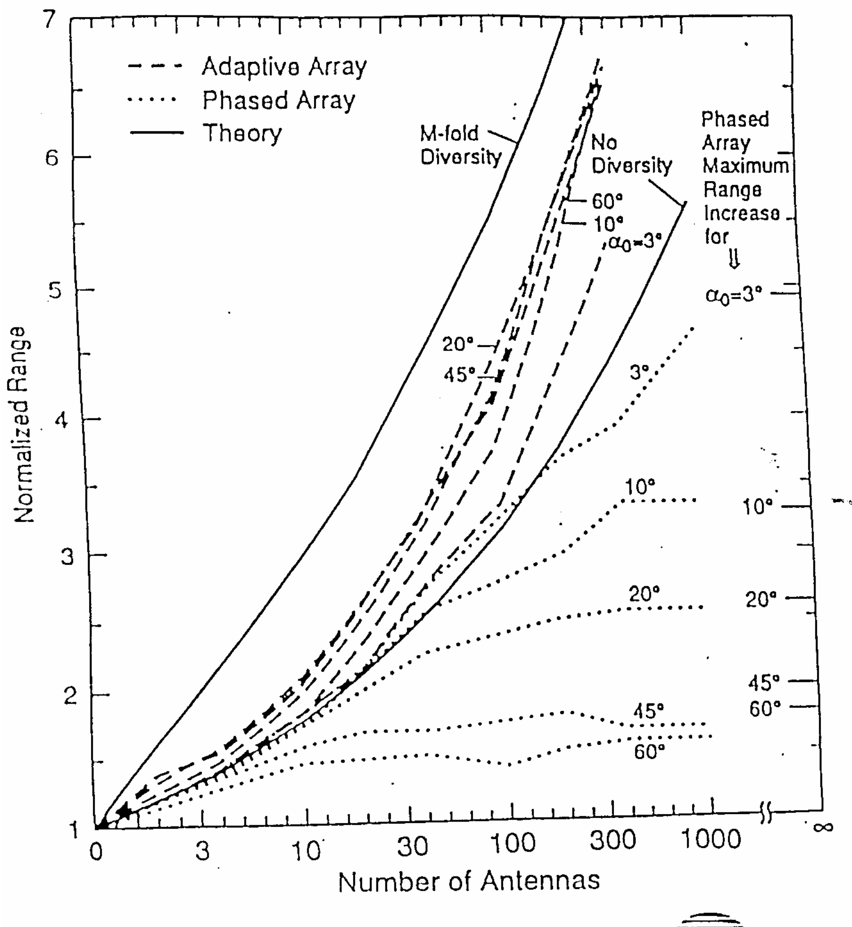
- With large scattering angle α, gain is limited for beamwidths $\approx \alpha$

MODEL



- Circular array of M cardioid-pattern antennas
- Uniformly-distributed, equal-power scatterers (20)
- $\gamma = 4$, no shadow fading
- For a 10^{-2} BER (averaged over 10,000 cases) with an omnidirectional antenna, and fixed transmit power and r, range is increased with M-element array until BER = 10^{-2}.
- $\lambda/2$ antenna spacing
- No delay spread

Range Increase for IS-136



Fixed Multibeam Antenna

- Increases gain for better coverage
- Range increase is limited by angular spread
- No spatial diversity gain
- Can be used on downlink or uplink

Adaptive Array

- Range increase independent of angular spread
- Diversity gain increases with antenna spacing
- Can be used on uplink with fixed multibeam downlink

CDMA

• 3-finger RAKE

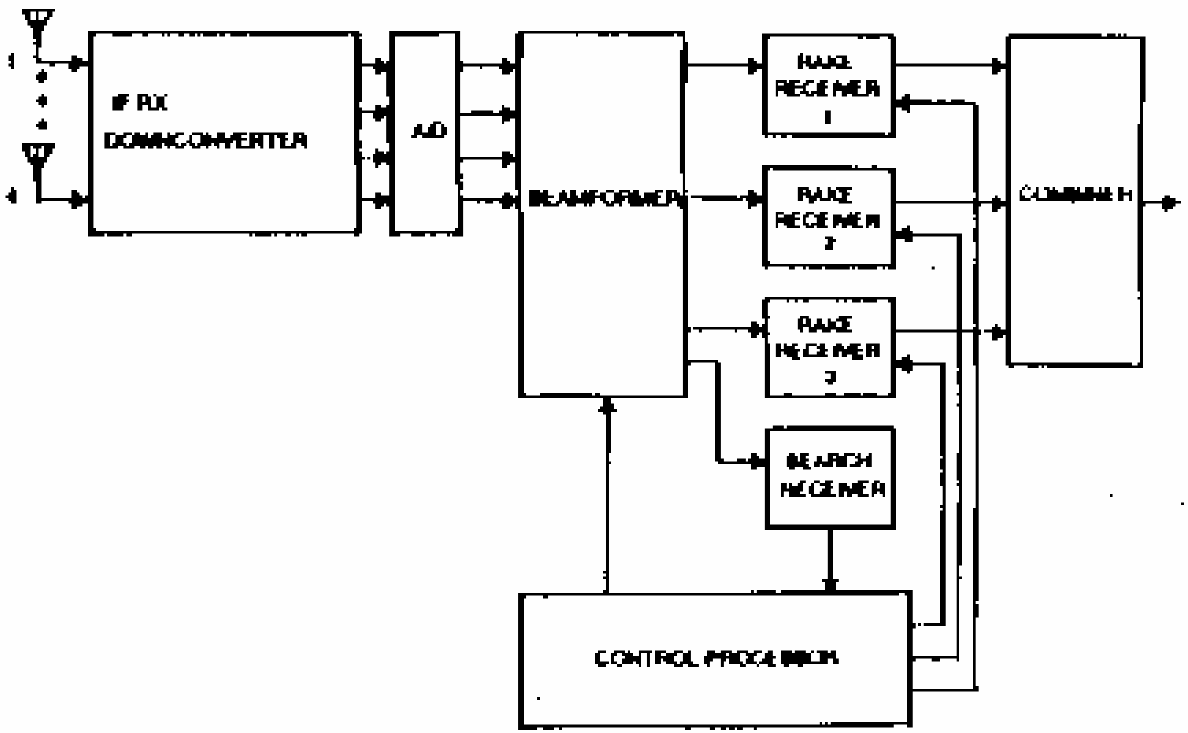
• Phased or adaptive array combining of RAKE outputs at each delay

• Maximal ratio combining of (summed over antennas) delayed RAKE outputs

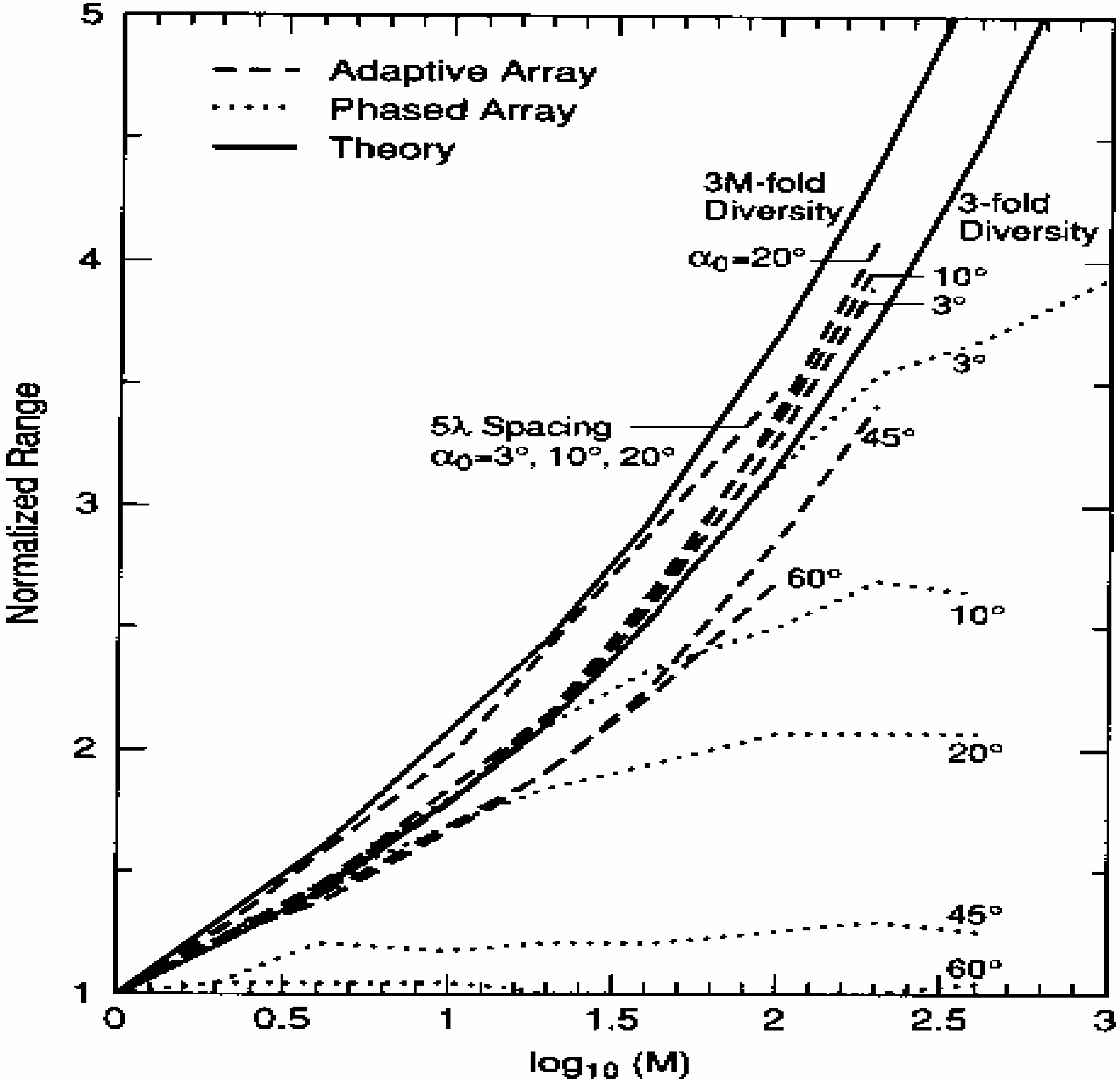
• *r* set for 3-symbol delay spread (e.g. r = 300ft at 5 Mbps)

• IS-95 picks different beams for each finger $\Rightarrow$ Less sensitive to scattering angle, and diversity gain with wider spacing not significant

CDMA with Adaptive Array

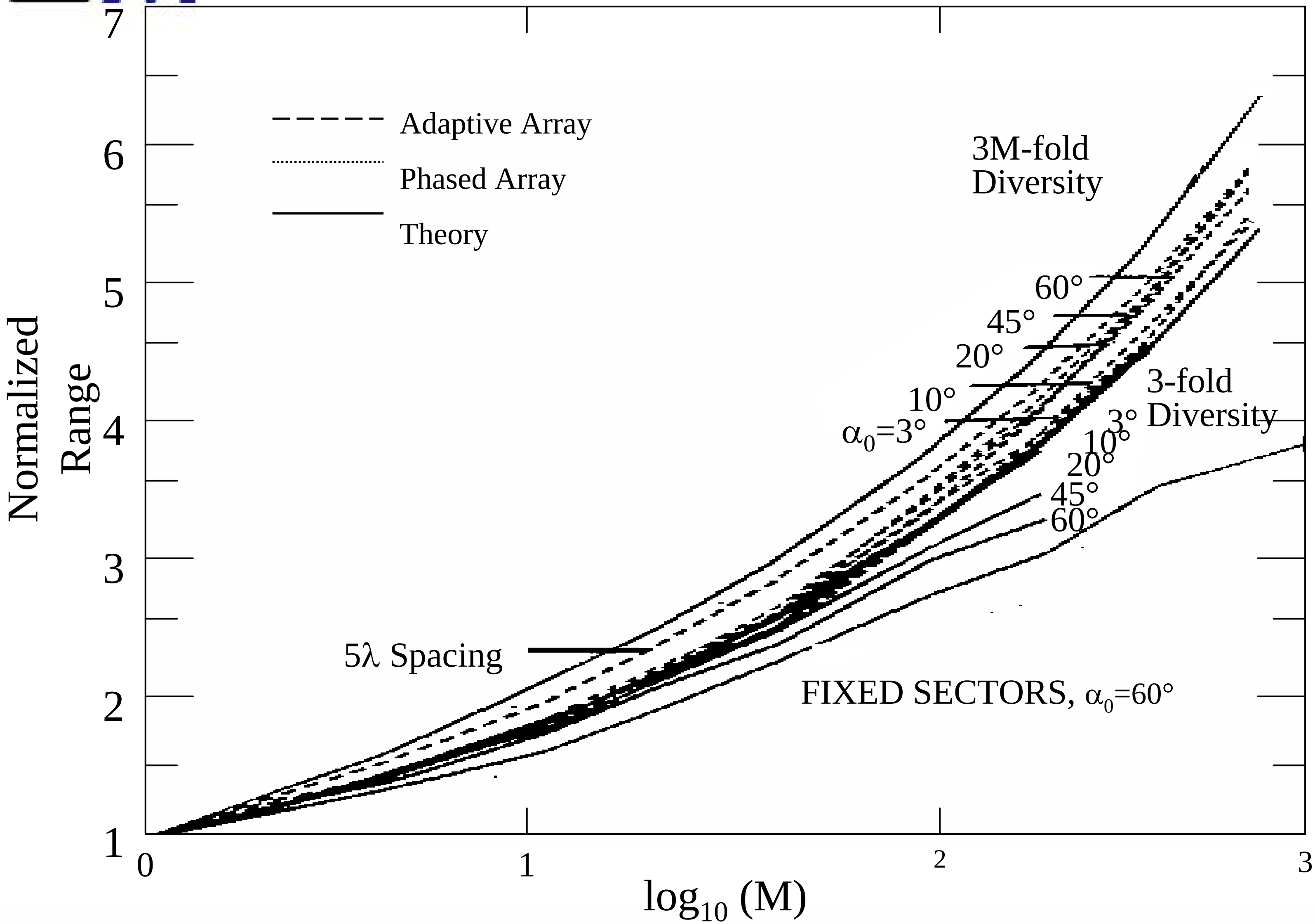


Range Increase with CDMA Signals



Single beam for all RAKE fingers results in range limitation with angular spread for multibeam antenna (phased array)

Range Increase with CDMA Signals - Different Beams per Finger



CONCLUSIONS FOR RANGE INCREASE

Phased Arrays:

• Range increase limitation determined by α, (with TDMA, rural areas with $M > 100$, urban areas with smaller M)

• With CDMA and RAKE, range increase degradation is much less

Adaptive Arrays:

• No range limitation

• Diversity gain with $\lambda/2$ spacing

• Full diversity gain with large M and a few λ spacing for $\alpha > 1°$

TDMA: Adaptive array with wide spacing (> M-fold increase in gain), but

- Downlink requires fixed beam approach (transmit diversity)
- Tracking at fading rate (184 Hz at 2 GHz)

CDMA: Fixed beam (M-fold increase in gain)

CAPACITY

CDMA

Phased Arrays:

• M-fold increase in capacity with M antennas through sectorization, with loss compared to M-fold increase only with large scattering angles and >3 dominant rays

• Tracking at beam switching rate (every few seconds)/same beam for transmission as reception

• Multiuser detection for greater capacity

Adaptive Arrays:

• Provide limited increase in capacity since number of interferers >> number of antennas (except for near-far problem/narrowband interferers)

$\Rightarrow$ Fixed beams

CAPACITY

TDMA

- Capacity is limited by a few dominant interferers

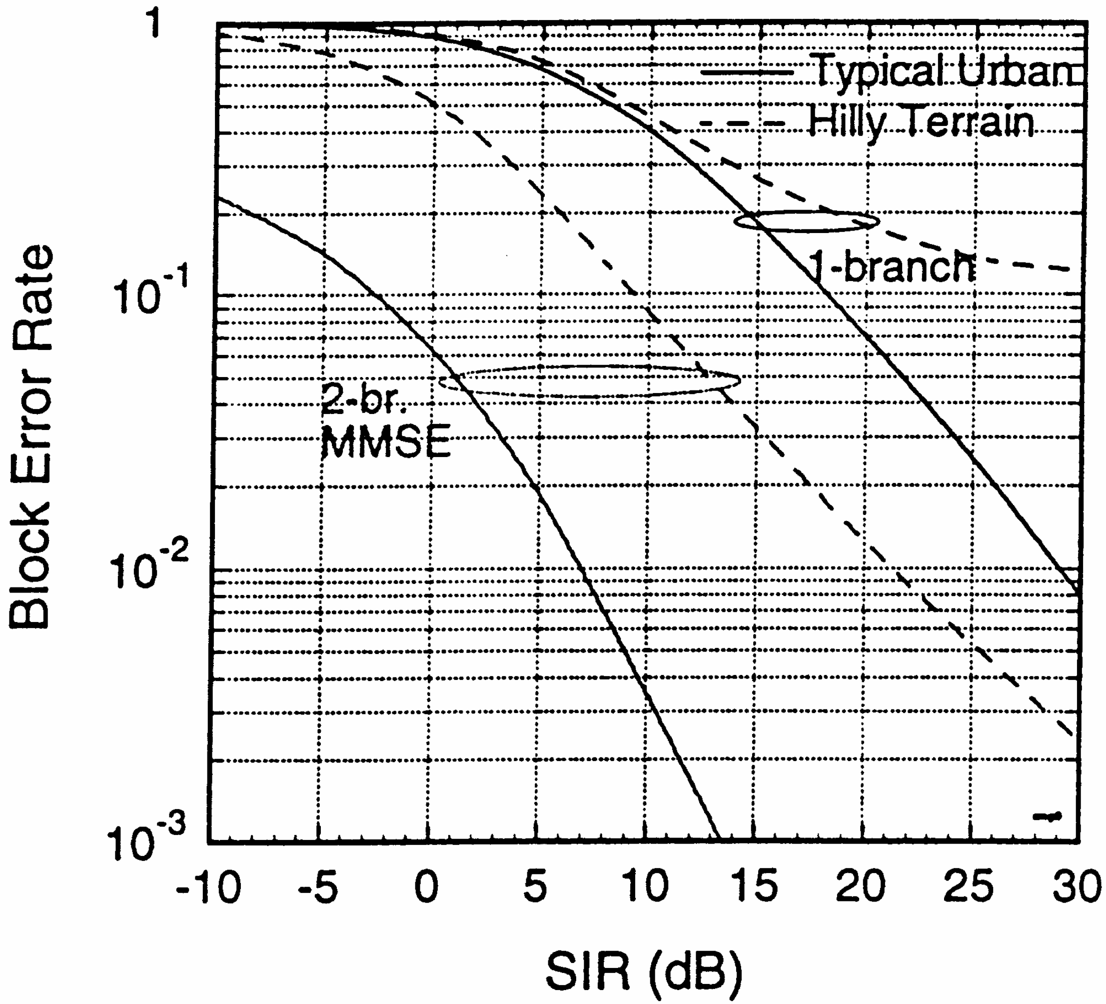
Phased Arrays: Some capacity increase - 2-fold with 4 beams

Adaptive Arrays: Large capacity increase on uplink with just a few antennas, but need fixed beams on the downlink $\Rightarrow$
adaptive array

SMART ANTENNAS IN 2G TDMA SYSTEMS

- **IS-136 TDMA:**
  - **On uplink, with two receive antennas, in 1999 changed from maximal ratio combining to optimum combining**
    - **Software change only - provided 3-4 dB gain in interference-limited environments**
    - **Combined with power control on downlink (software change only) - increased capacity through frequency reuse reduction**
  - **Use of 4 antennas (adaptive array uplink/multibeam, with power control, downlink) extends range and/or doubles capacity (N=7 to 4 or 3)**

ADAPTIVE ARRAYS IN EDGE

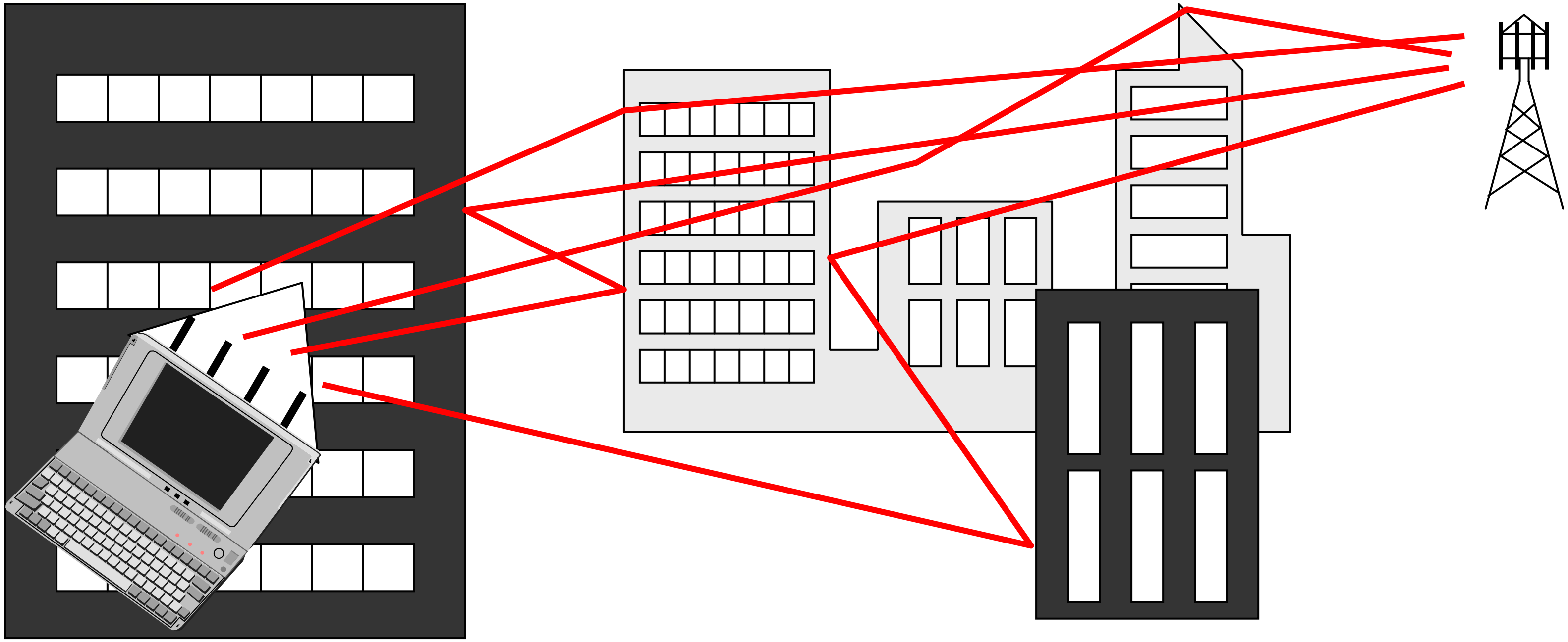


CONCLUSIONS FOR CAPACITY INCREASE

TDMA: Adaptive arrays provide > *M*-fold capacity increase

CDMA: Fixed beams provide ≈ *M*-fold capacity increase

Multiple-Input Multiple-Output (MIMO) Radio



- With M transmit and M receive antennas, can provide M independent channels, to increase data rate M-fold with no increase in total transmit power (with sufficient multipath) – only an increase in DSP
  - Indoors – up to 150-fold increase in theory
  - Outdoors – 8-12-fold increase typical
- Measurements (e.g., AT&T) show 4x data rate & capacity increase in all mobile & indoor/outdoor environments (4 Tx and 4 Rx antennas)
  - 216 Mbps 802.11a (4X 54 Mbps)
  - 1.5 Mbps EDGE
  - 19 Mbps WCDMA

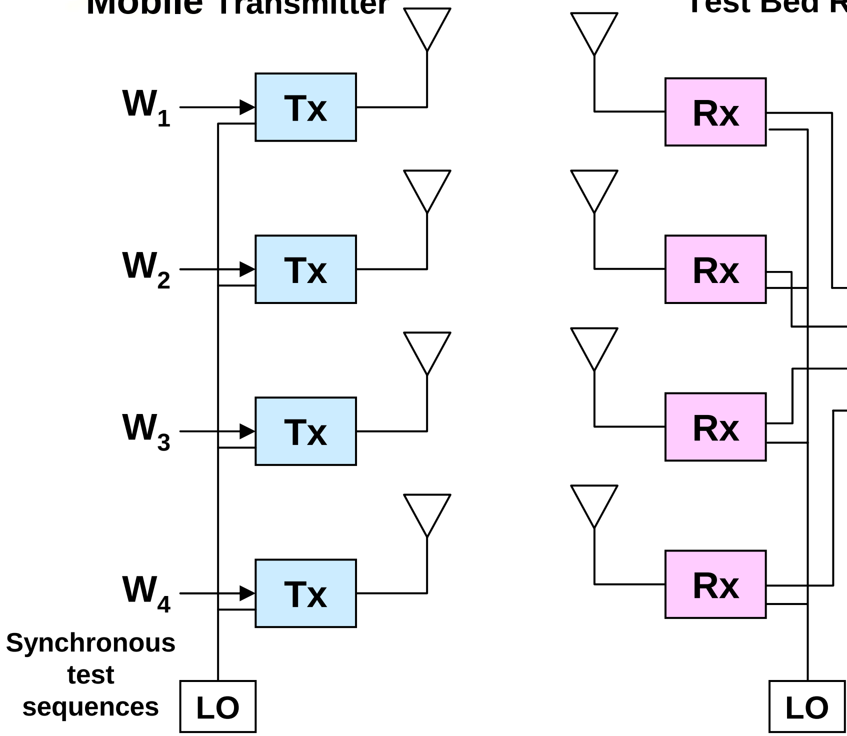
MIMO-EDGE

- **Goal: 4 transmit / 4 receive antennas in EDGE can theoretically increase capacity 4-fold with the same total transmit power (3.77X384 kbps = 1.45 Mbps is actual theoretical increase)**
- **Issues:**
  - **Joint spatial-temporal equalization**
  - **Weight adaptation**
  - **Mobile channel characteristics to support MIMO-EDGE**
- **AT&T approach:**
  - **Development of multi-antenna EDGE testbed**
  - **Development of 2X2 and 4X4 DDFSE architecture with MMSE combining using successive interference cancellation**
  - **Mobile channel measurements**

MIMO Channel Testing

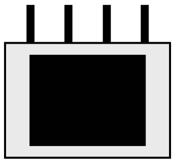
Mobile Transmitter

Test Bed Receiver with Rooftop Antennas

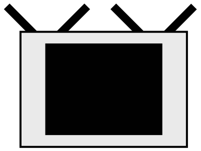


- Record complex correlation of each transmit waveform on each receive antenna, C_{4x4}
- Compute C^HC correlation matrix to determine potential capacity and predict performance
- Compute fading correlation across receive array

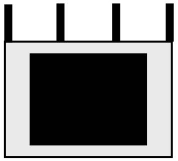
Transmit Antenna Configurations



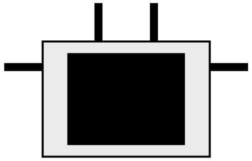
Space diversity



Space / polarization diversity



Space / pattern diversity



Space / polarization / pattern diversity

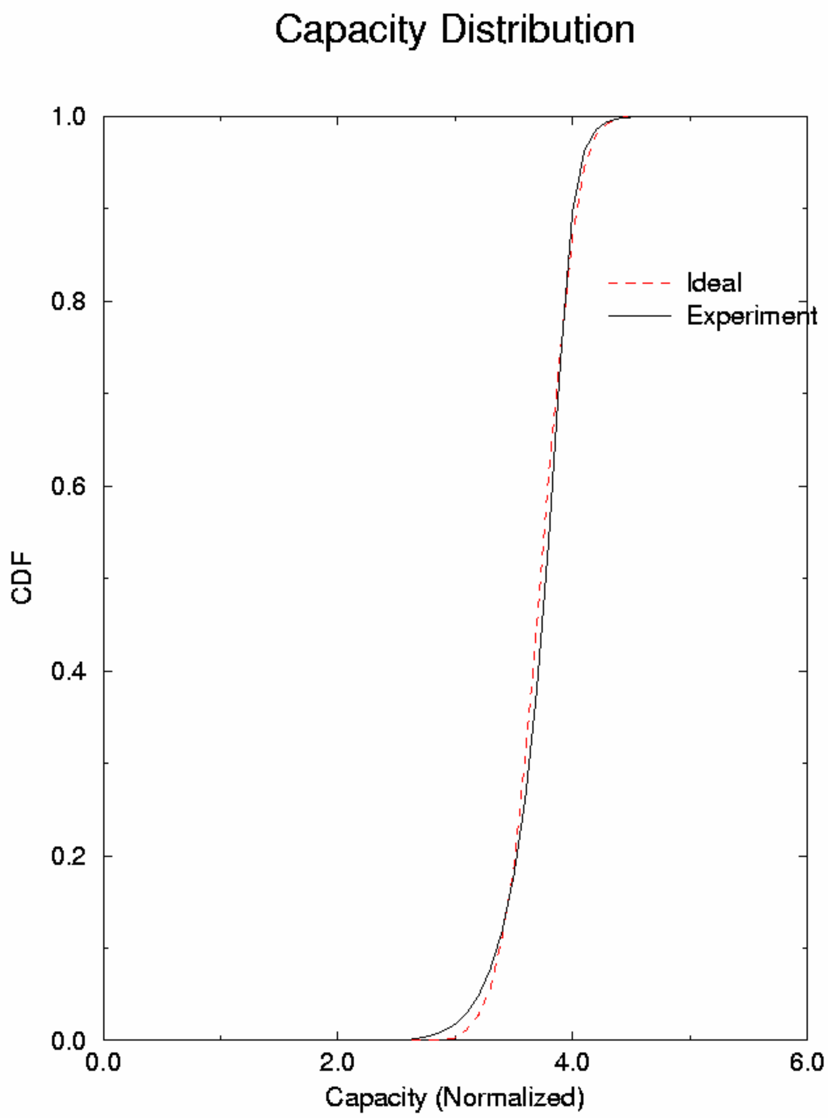
MIMO Channel Measurement System

Transmitter

- **4 antennas mounted on a laptop**
- **4 coherent 1 Watt 1900 MHz transmitters with synchronous waveform generator**

Receive System

- **Dual-polarized slant 45° PCS antennas separated by 10 feet and fixed multibeam antenna with 4 - 30° beams**
- **4 coherent 1900 MHz receivers with real-time baseband processing using 4 TI TMS320C40 DSPs**



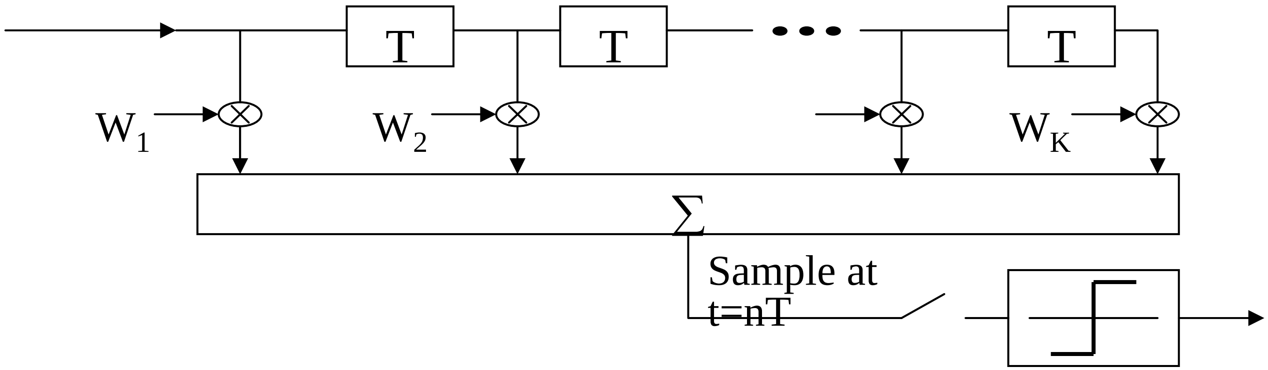
Capacity Distribution
1.0
0.8
0.6
0.4
0.2
0.0
CDF
0.0
2.0
4.0
6.0
Capacity (Normalized)
Ideal
Experiment

ISSUES

- Equalization
- Correlation
- Downlink/Portable Antennas
- Multipath Distribution

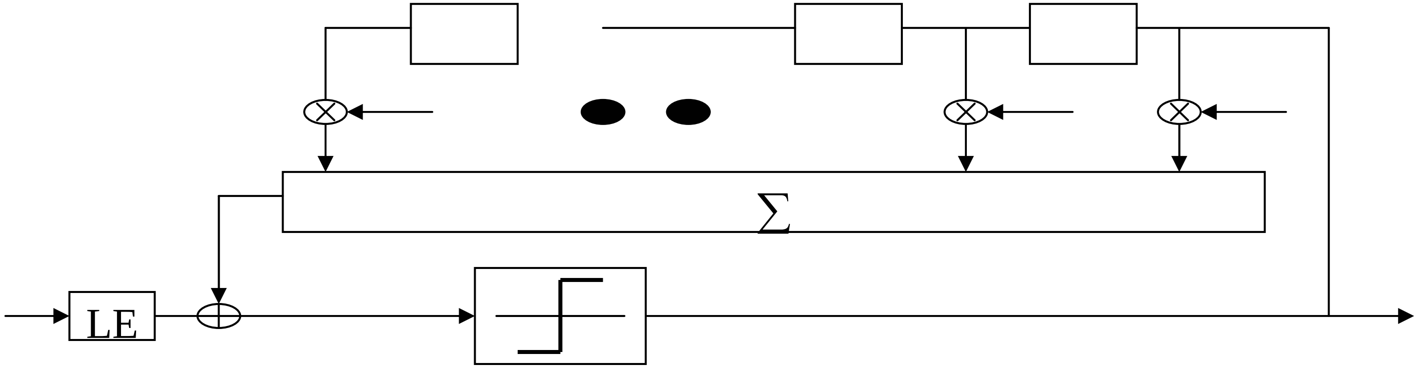
EQUALIZATION

Linear equalization (LE)



- Inverts the channel $\quad H_R(f) = H_C^{-1}(f)$
- Delay may be less than T for FSE if BW > 1/T
- Advantages:
  - Easy to implement and analyze
- Disadvantages:
  - Noise enhancement
  - May require many taps (e.g. $K = \infty$ with double spike)
- Poor performance compared to nonlinear techniques

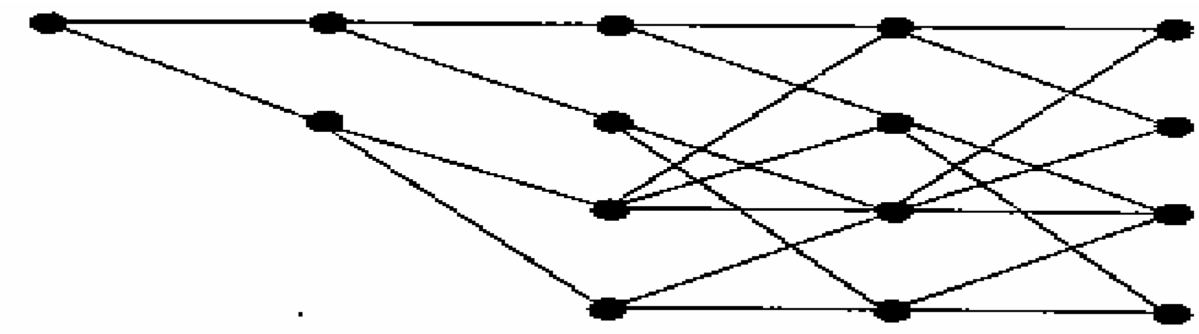
DECISION FEEDBACK EQUALIZER (DFE)



- Advantages:
  - Easy to implement
  - No noise enhancement
  - # taps ≈ D
- Disadvantages:
  - Error propagation
  - Subtracts ISI portion (loss in signal power)

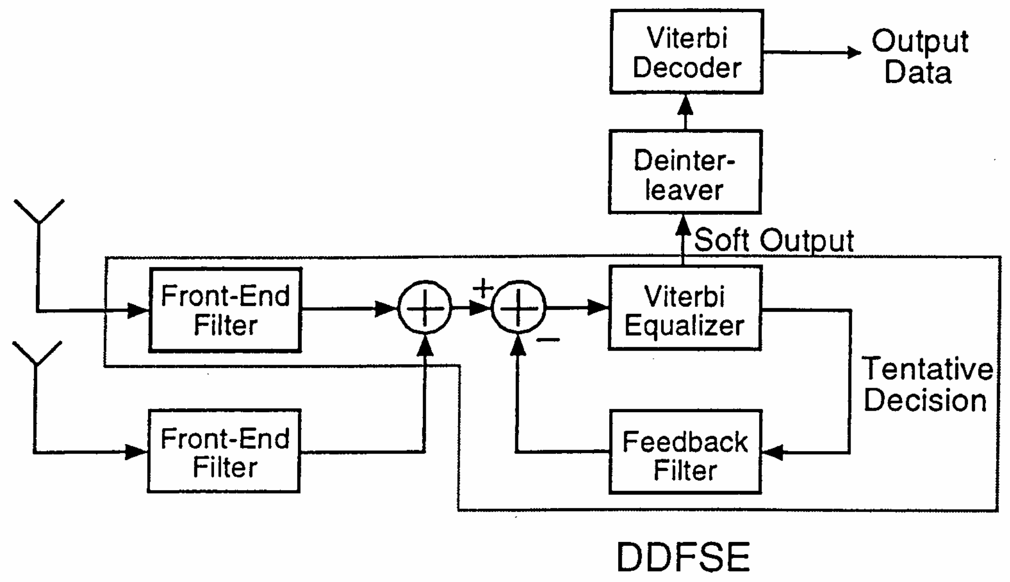
MAXIMUM LIKELIHOOD SEQUENCE ESTIMATION (MLSE)

- Chooses sequence of symbols with MMSE



- Typically implemented by Viterbi algorithm
- Advantages:
  - Optimum technique
  - Utilizes all received signal power
- Disadvantages:
  - Complex to implement (# states in trellis grows exponentially with delay and # signal levels) and analyze

Spatial-Temporal processing using DDFSE for interference suppression



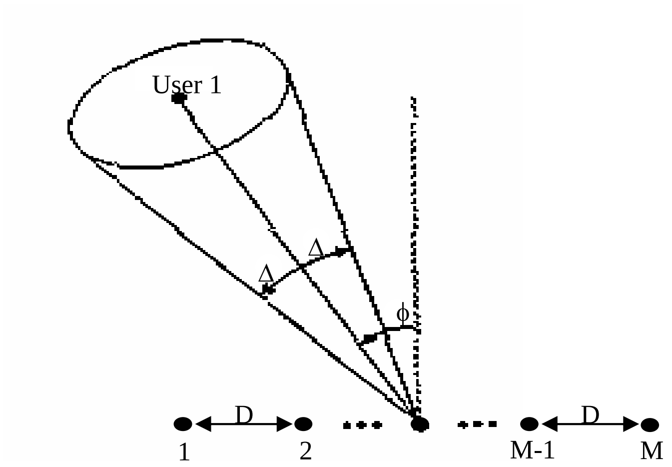
Issues: tracking, dual antenna terminals

CORRELATION

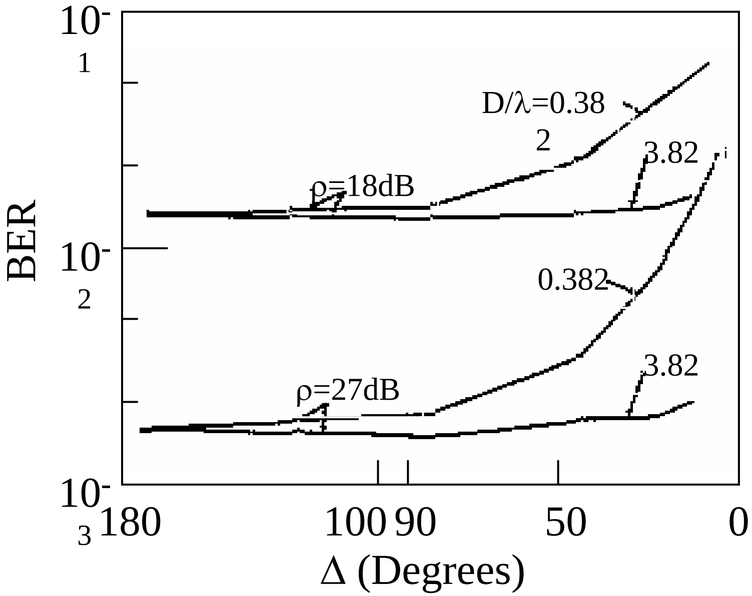
• Degradation due to fading correlation with adaptive array that combats fading, suppresses interference, and equalizes delay spread is only slightly larger than that for combating fading alone:

- Small degradation with correlation less than 0.5

Model



BER with Correlation



TRANSMIT DIVERSITY

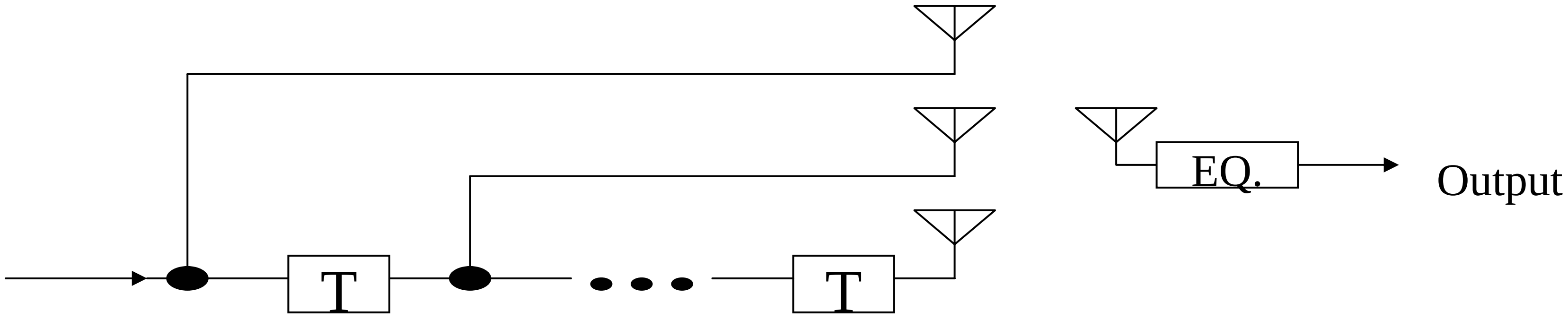
1) If same channel is used for transmitting and receiving (TDMA/TDD or FDD within coherence bandwidth

- Adaptive retransmission
  - Selection diversity: transmit with best receive antenna
  - Maximal ratio combining: transmit with same antenna pattern as receive to maximize receive signal power
  - Optimum combining: transmit with receive antenna pattern to increase receive signal power while reducing interference to other users

2) If feedback from receiver is possible:

- Switched diversity with feedback - single bit feedback with propagation delay

3) Create ISI and then equalize



• With MLSE, two transmit antennas give 2-fold diversity [Seshadri and Winters, JWIN '94]

TRANSMIT DIVERSITY

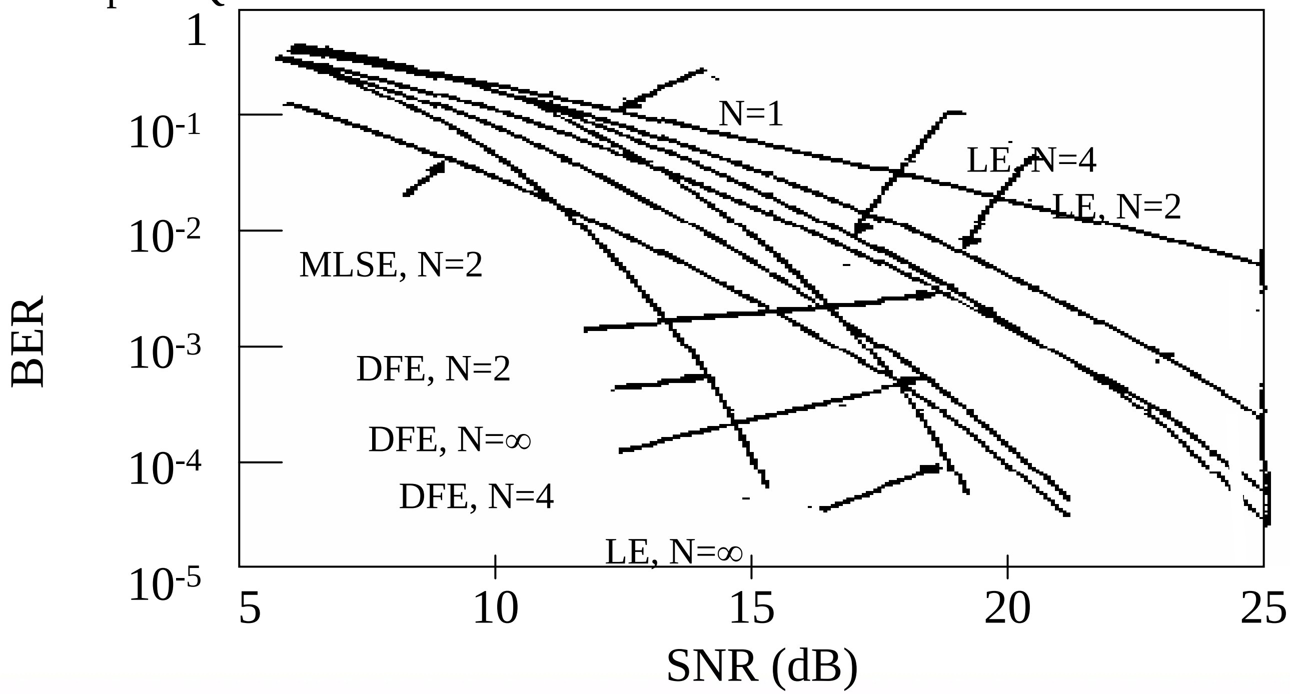
Can use transmit diversity to obtain adaptive antenna improvement with transmit antennas:

• Create ISI with time delay between transmit antennas and equalize at receiver

• Diversity gain is (transmit antennas) x (receive antennas) - multiple remote antennas may not be needed

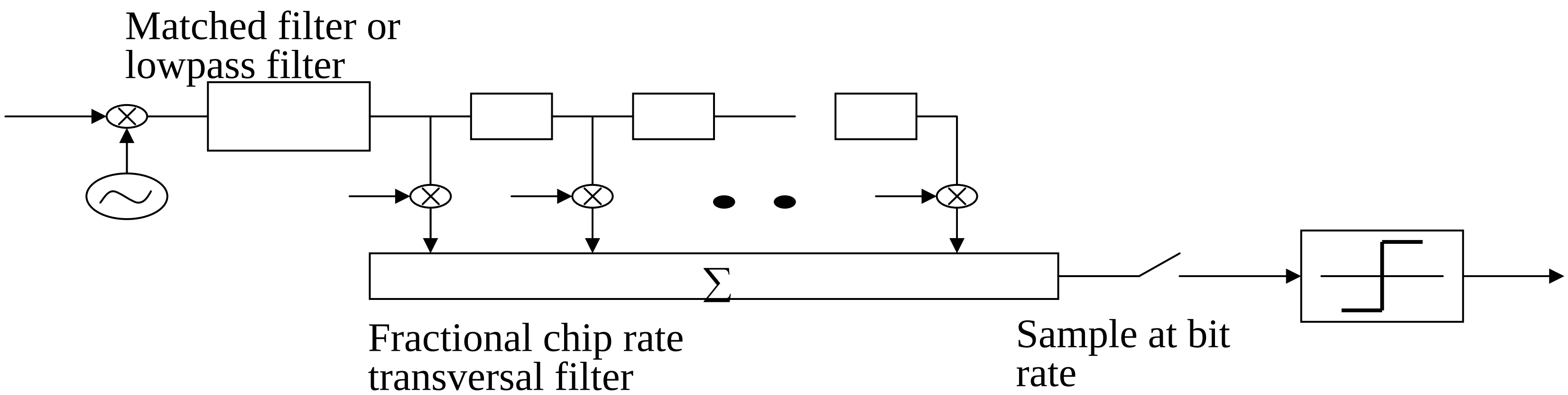
• Interference suppression is also possible (if interferers use same method)

•Example - QPSK with *N* Transmit Antennas



CDMA

- RAKE receiver - resolves multipath at chip duration



- Transmit diversity creates frequency selective fading even without delay spread (eg. indoors) [Viterbi and Padovani, Communications Magazine, 1992]

4) Create fast fading with frequency offset between transmit antennas (M-fold diversity gain with interleaving and coding)

MULTIPATH DISTRIBUTION

Distribution of multipath around antennas significantly impacts fixed beam and adaptive array approaches for

- Range increase in TDMA on downlink
- Capacity increase in CDMA
- Delay spread reduction
- Multipath fading tracking methods

If multipath is uniformly distributed in angle-of-arrival for both strength and delay, these gains are not possible

But:

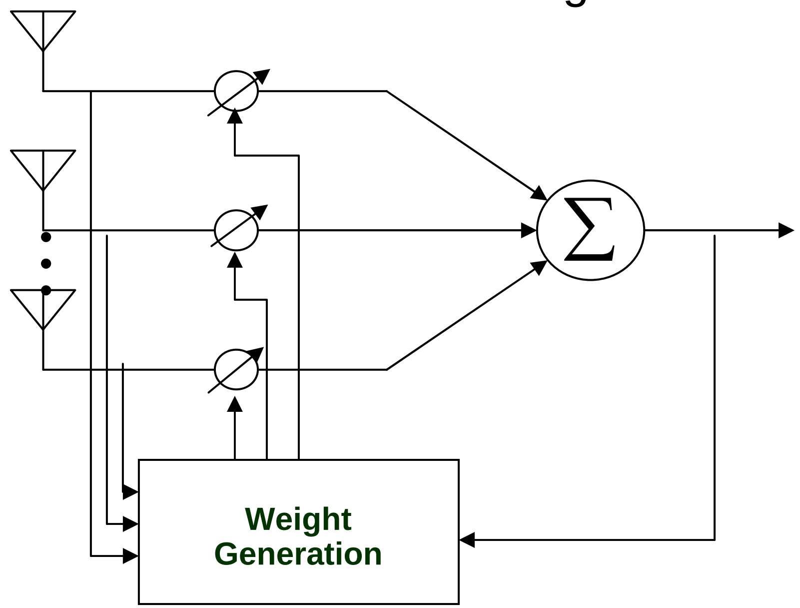
- Generally, there are only a few dominant paths

$\Rightarrow$ Large impact of model on performance

$\Rightarrow$ Multipath can be beneficial for MIMO techniques

WEIGHT GENERATION TECHNIQUES

For Smart Antenna: Need to identify desired signal and distinguish it from interference



Blind (no demod): MRC – Maximize output power
Interference suppression – CMA, power inversion, power out-of-band

Non-Blind (demod): Training sequence/decision directed reference signal
MIMO needs non-blind, with additional sequences

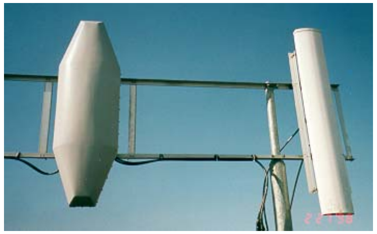
Motia

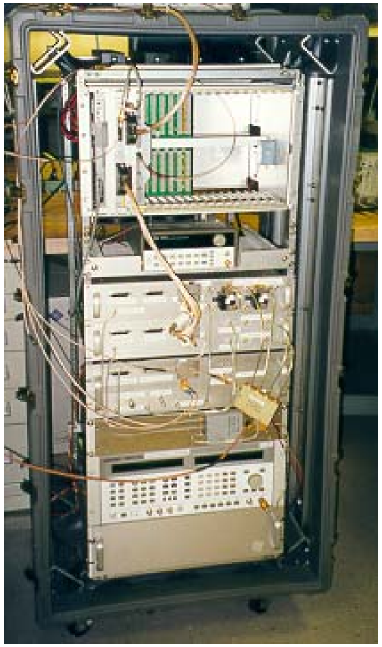
Smart Antennas in Cellular Systems

- Smart antennas for WCDMA can provide significant gains (>7 dB at handset)
  - But not justified today (Innovics, Metawave) (Qualcomm is implementing, though)
- MIMO for WCDMA may be implemented in 2-5 years

Motia

Smart Antenna System

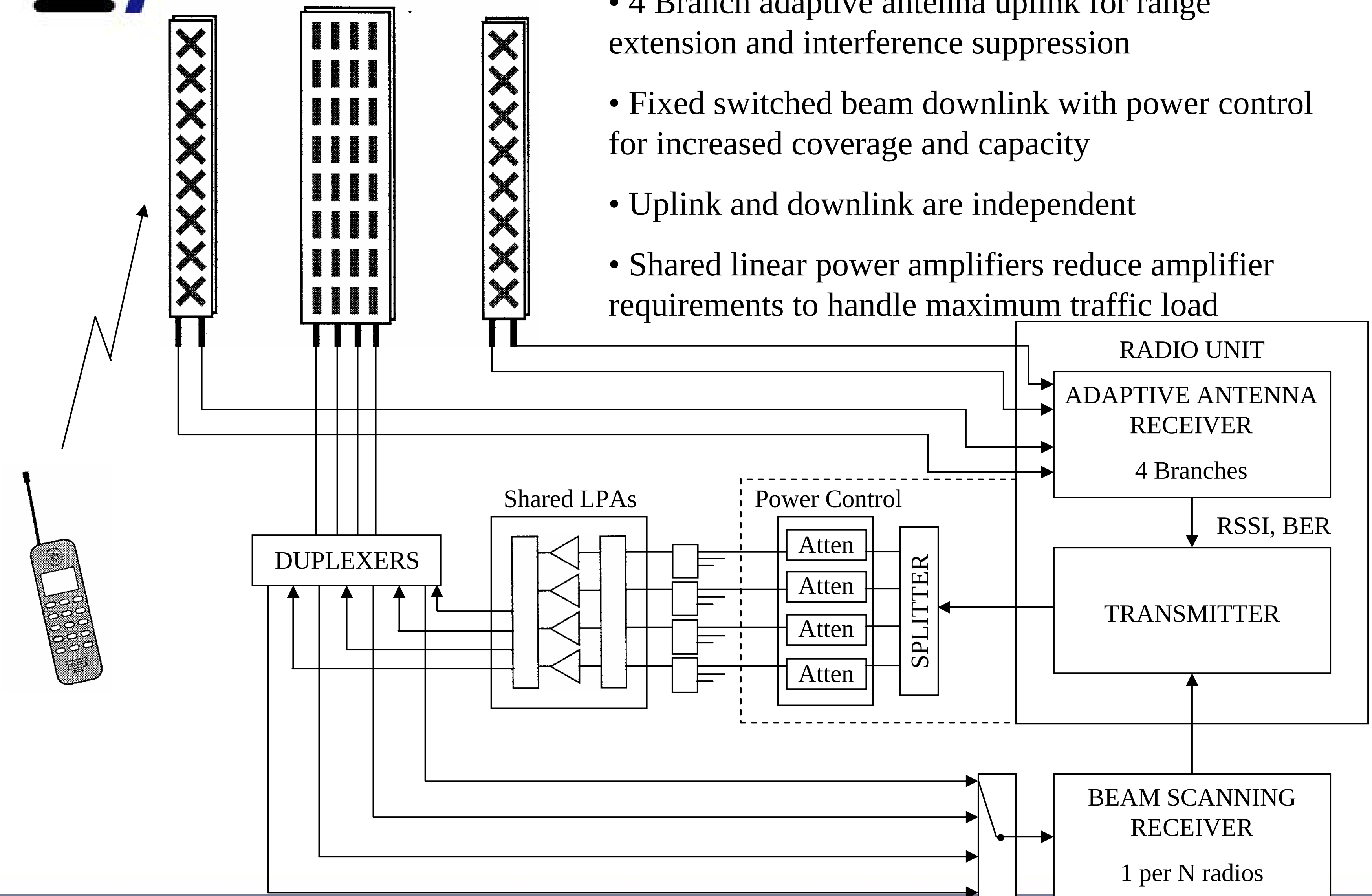




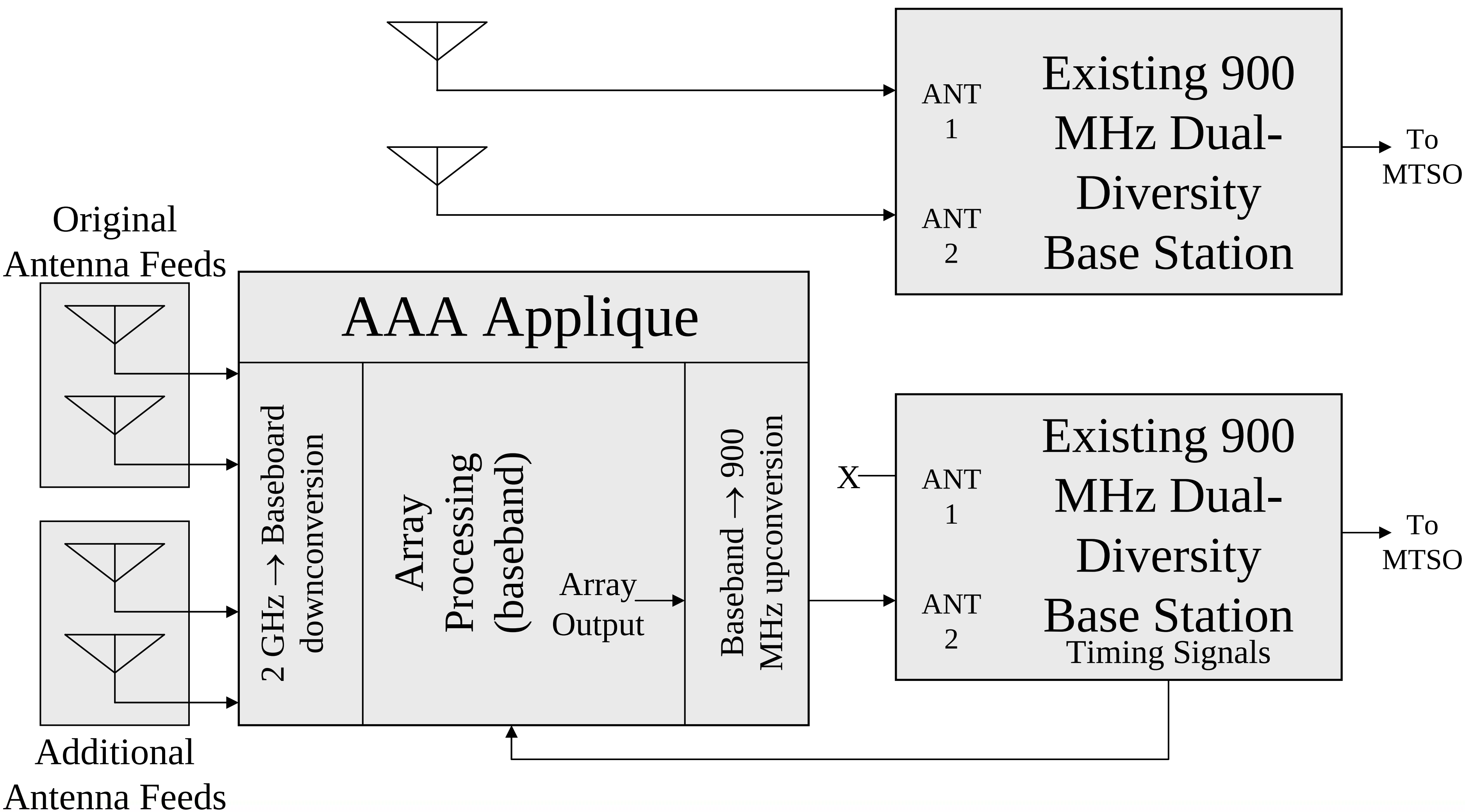
- Dual-polarized slant 45° PCS antennas separated by 10 feet and fixed multibeam antenna with 4 - 30° beams
- 4 coherent 1900 MHz receivers with real-time baseband processing using 4 TI TMS320C40 DSPs

IS-136 Smart Antenna System

- 4 Branch adaptive antenna uplink for range extension and interference suppression
- Fixed switched beam downlink with power control for increased coverage and capacity
- Uplink and downlink are independent
- Shared linear power amplifiers reduce amplifier requirements to handle maximum traffic load



Applique Architecture

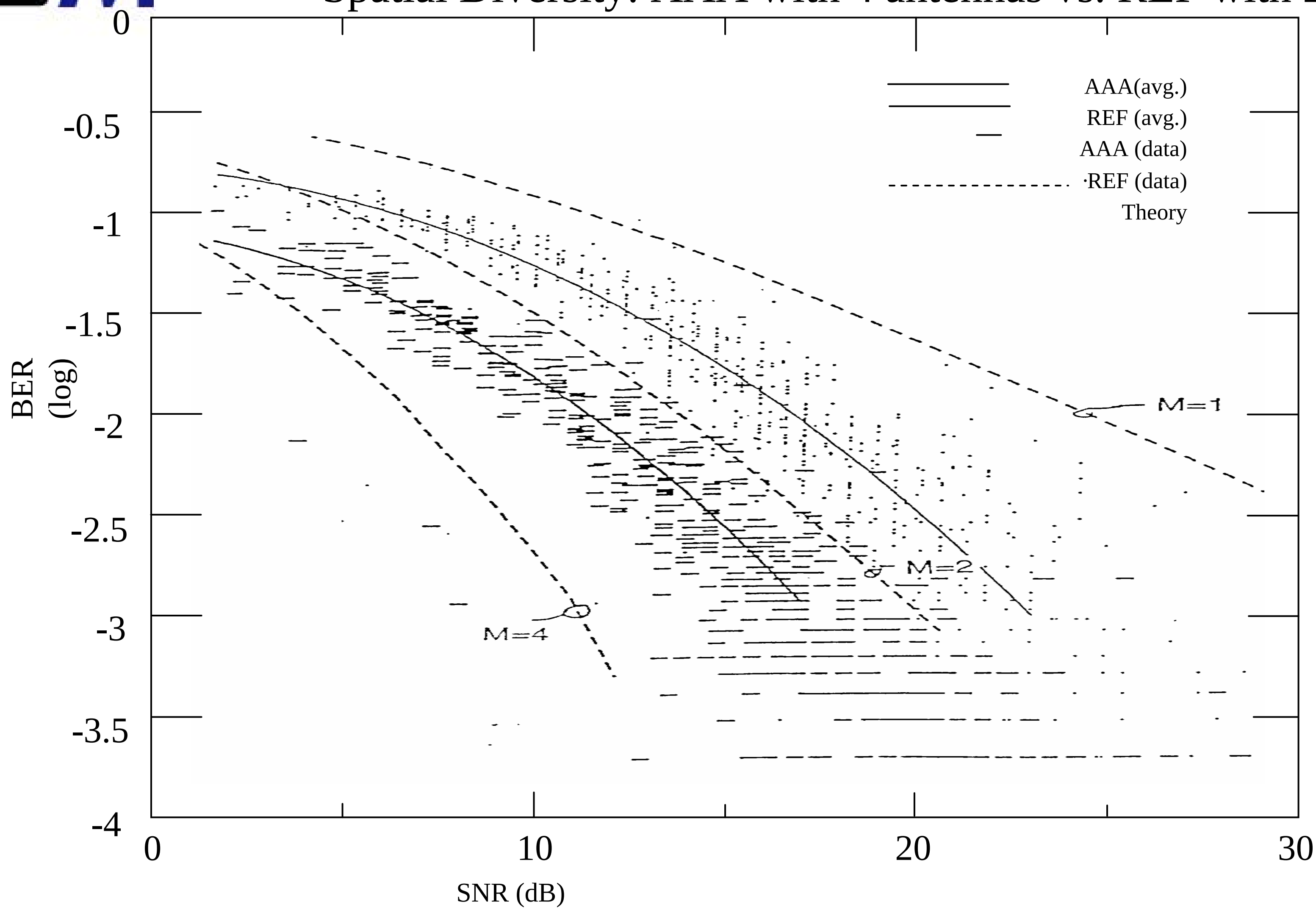


EXPERIMENTAL TESTBED

- 1.9 GHz PCS band, IS-136
- 4 antennas (adaptive array uplink / multibeam downlink)
- Baseband processing: 4 ‘C40 DSP’s
- DMI - realtime (symbol-by-symbol) processing with sliding window and symbol synchronization (uplink)
- RF channel emulator (independent Rayleigh fading)
- Ideal (theoretical) performance at 10^{-2} BER (versus 2 antenna system with selection diversity):
  - 6 dB gain in noise alone ($S/I = \infty$)
  - 4 dB gain with $S/I = 0$ dB
- Experimental Results:
  - Noise alone ($S/I = \infty$): < 0.5 dB implementation loss up to 60 mph
  - $S/I = 0$ dB: 1dB implementation loss for speeds < 8 mph, close to 10^{-2} BER at high S/N at 60 mph

RANGE EXTENSION

Spatial Diversity: AAA with 4 antennas vs. REF with 2 antennas

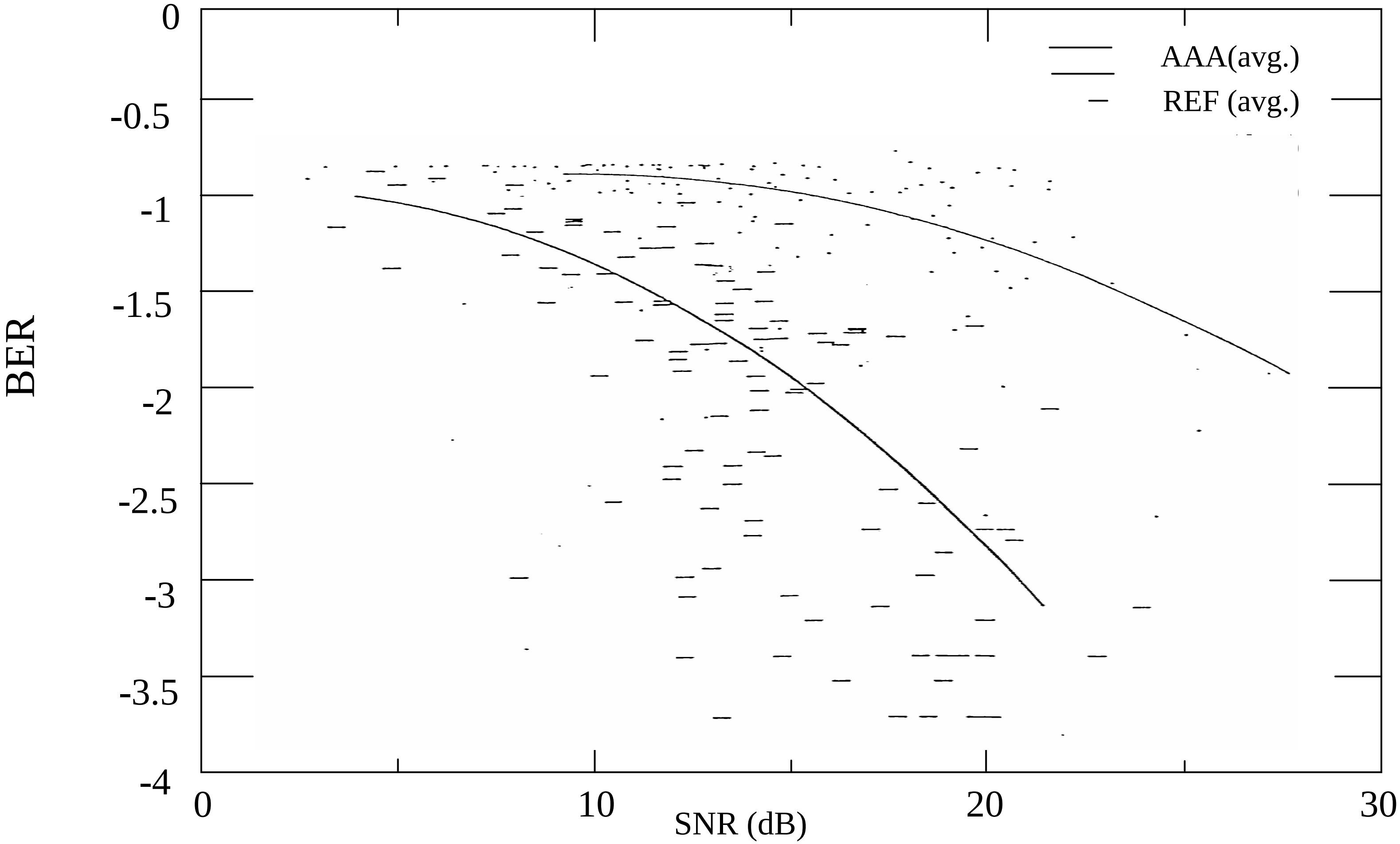


RANGE EXTENSION RESULTS

Diversity Type	Adaptive Array	Gain at 10^{-2} BER over Reference
Space	4 equally-spaced (12’)	4.2 dB
Pol./Space	2 (12’) dual pol (45)	4.4 dB
Pol./Angle	2 (18”) dual pol (45)	2.9 dB
Angle	4 (before Butler matrix)	1.1 dB

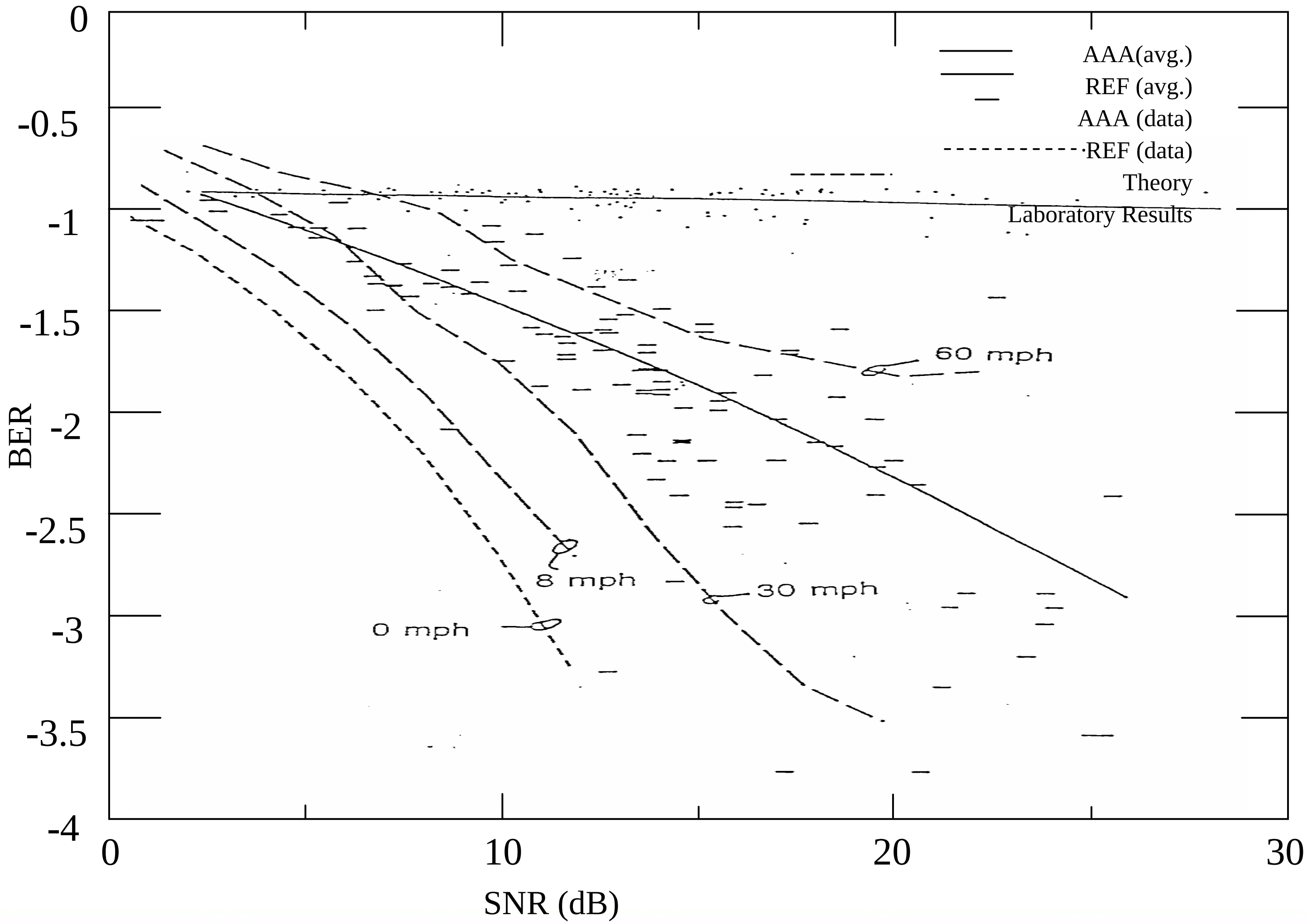
INTERFERENCE SUPPRESSION
- OFFSET INTERFERER

Spatial Diversity: S/I = 0dB, AAA with 4 antennas vs. REF with 2 antennas



INTERFERENCE SUPPRESSION - ADJACENT INTERFERER

Spatial Diversity: S/I = 0dB, AAA with 4 antennas vs. REF with 2 antennas



Interference Suppression Results for Required SNR

Case	Diversity Type	S/N (dB) @ BER = 0.01		
		REF	AAA	GAIN
Adj., S/I=0dB	Spatial	-	21.5	*
	Pol./Spatial	-	17.1	*
	Pol./Angle	-	23.2	*
	Angle	*	-	*
Offset, S/I=0dB	Spatial	28.5	15.6	12.9
	Pol./Spatial	-	16.6	*
	Pol./Angle	-	18.2	*
	Angle	*	23.6	*

- Can’t be achieved for SNR < 30dB

* Not determined

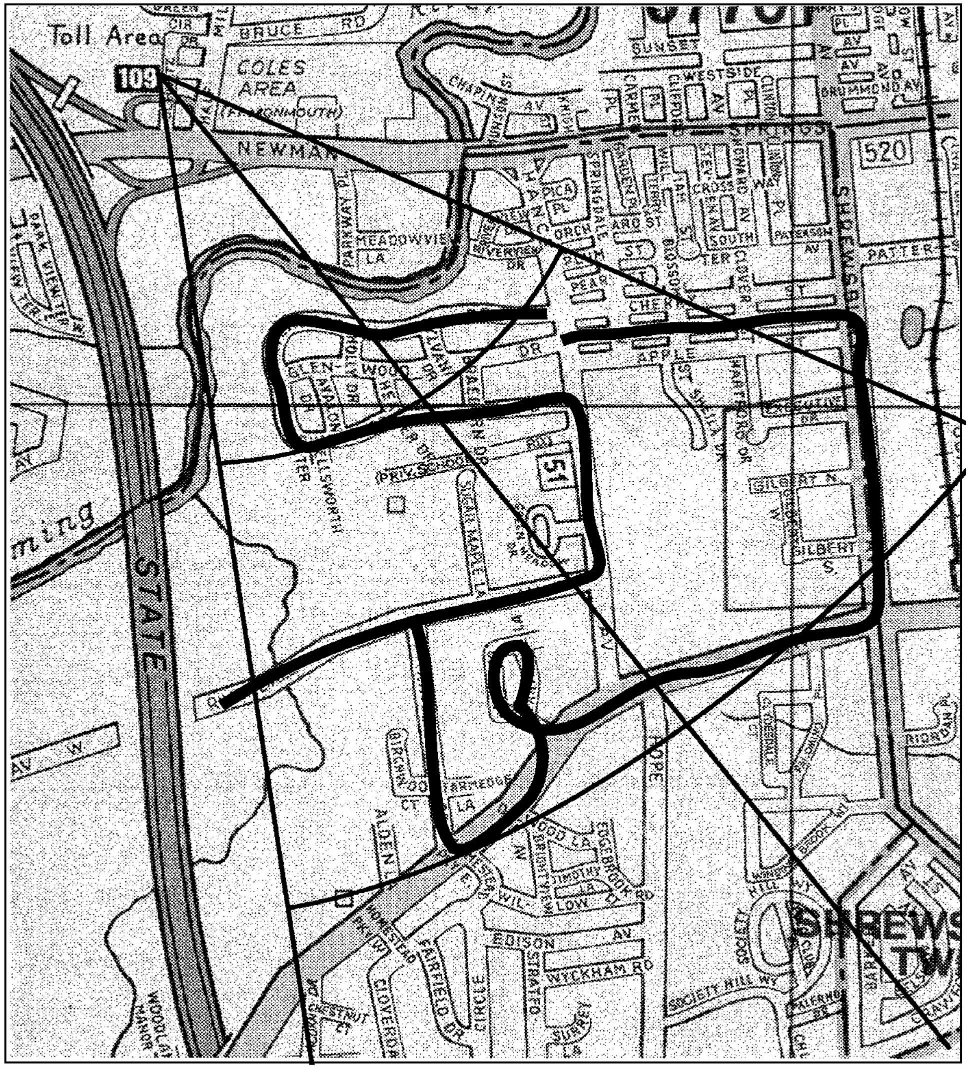
Interference Suppression Results for Required S/I

Offset Interferer Only

Diversity Type	S/I (dB) @ BER = 0.01		
	REF	AAA	GAIN
Spatial	17.5	2.4	15.1
Pol./Spatial	18.0	4.6	13.4
Pol./Angle	19.5	7.0	12.5
Angle	*	11.9	*

* Not determined

Field Test Drive Route



- 60° drive route within coverage of two center beams and 65° dual pol antennas
- Non line-of-sight conditions along route
- Suburban environment with gently rolling terrain
- Sense residential area with 2 story houses and tall trees
- Open area with office parks
- Maximum downrange distance of 2.5 miles
- Peak speed of 45 mph, average speed of 30 mph

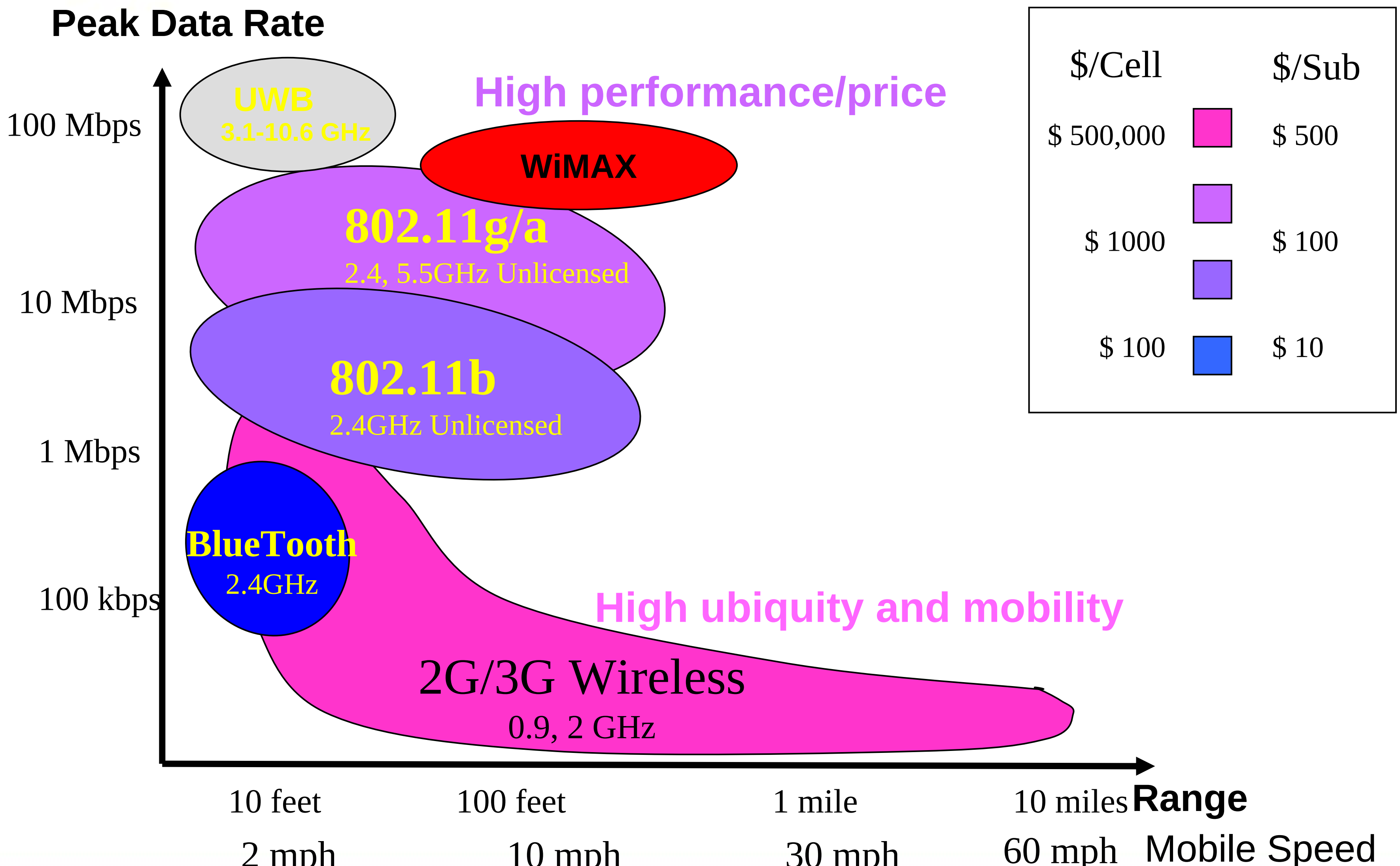
FIELD TEST CONCLUSIONS

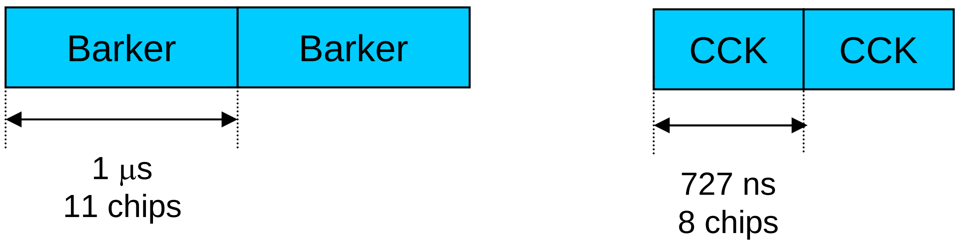
Experimental results with 4 antennas and real-time implementation show low implementation loss for

- 6 dB gain increase for 40% greater range

- Operation with an equal power interferer with potential to more than double capacity with rapid fading

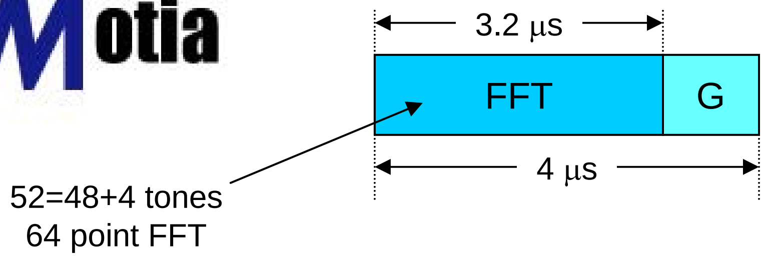
OTHER WIRELESS APPLICATIONS





Key 802.11b Physical Layer Parameters:

Data rate:	1, 2, 5.5, 11 Mbps (adaptation to our needs for 1 Mbps only)
Modulation/Spreading:	Direct Sequence Spread Spectrum (DSSS)
Transmission modes: (dynamic rate shifting)	• DBPSK, DQPSK with 11-chip Barker code (1, 2 Mbps) (this mode stems from the original 802.11 standard) • 8-chip complementary code keying (CCK) (5.5, 11 Mbps) • optional: packet binary convolutional coding (PBCC), 64 state, rate 1/2 CC (BPSK 5.5 Mbps, QPSK 11 Mbps)
Chip rate:	11 MHz
Frequency band:	Industrial, Scientific and Medical (ISM, unlicensed) 2.4 - 2.4835 GHz
Bandwidth:	22 MHz - TDD
Channel spacing:	5 MHz
Number of channels:	Total of 14 (but only the first 11 are used in the US)
Carrier accuracy:	±25 ppm



Key 802.11a Physical Layer Parameters:

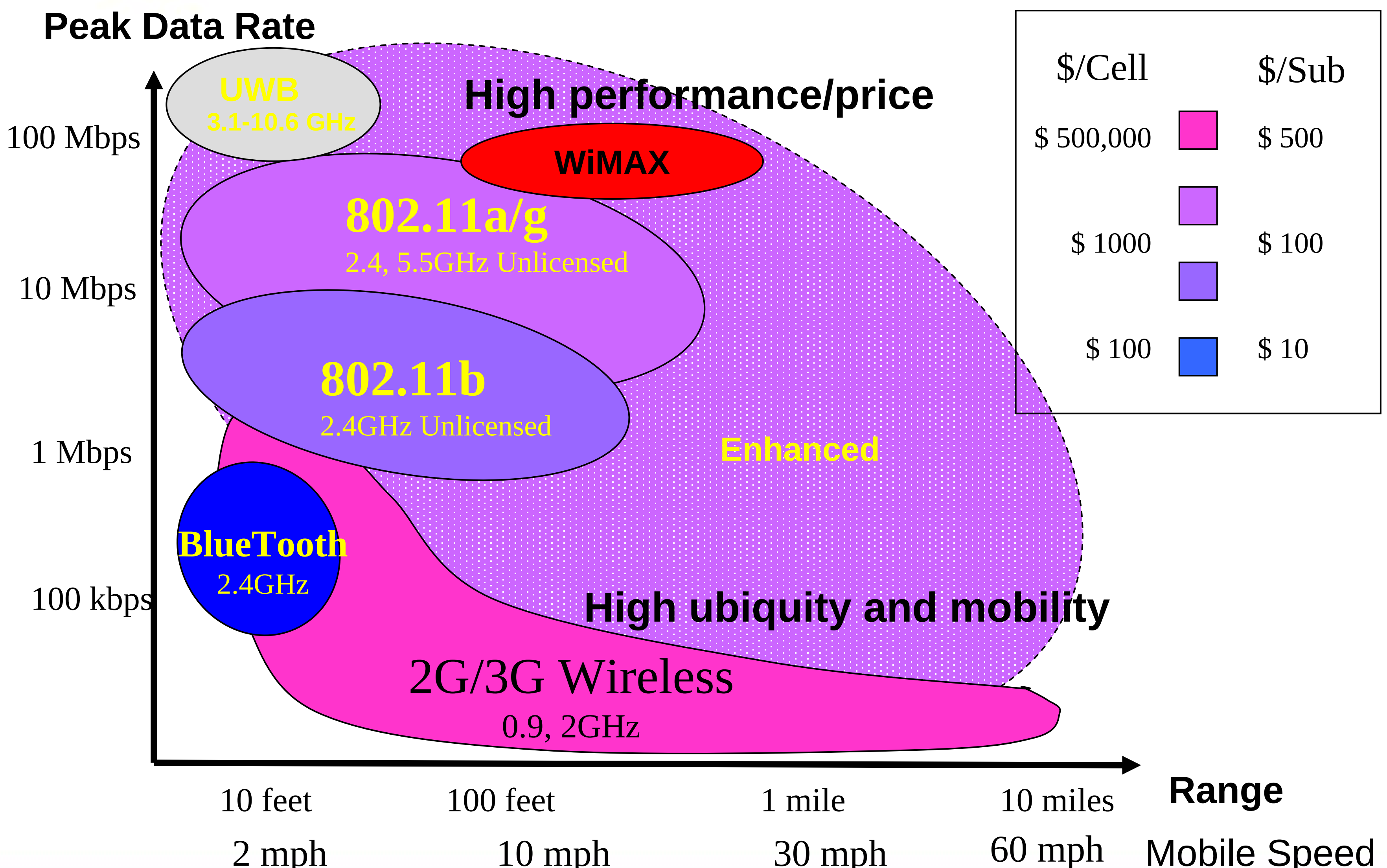
Data rate:	6, 9*, 12, 18*, 24, 36*, 48*, 54* Mbps
Modulation:	BPSK, QPSK, 16QAM, 64QAM*
Coding rate:	1/2, 2/3, 3/4*
Subcarriers:	52
Pilot subcarriers:	4
FFT size:	64
Symbol duration:	4 μs
Guard interval:	800 ns
Subcarrier spacing:	312.5 kHz
Bandwidth:	16.56 MHz - TDD
Channel spacing:	20 MHz
Frequency band:	Unlicensed national infrastructure (U-NII)
Number of channels:	Total of 12 in three blocks between 5 and 6 GHz
Carrier accuracy:	20 ppm
Carrier accuracy @5.8GHz:	114 kHz

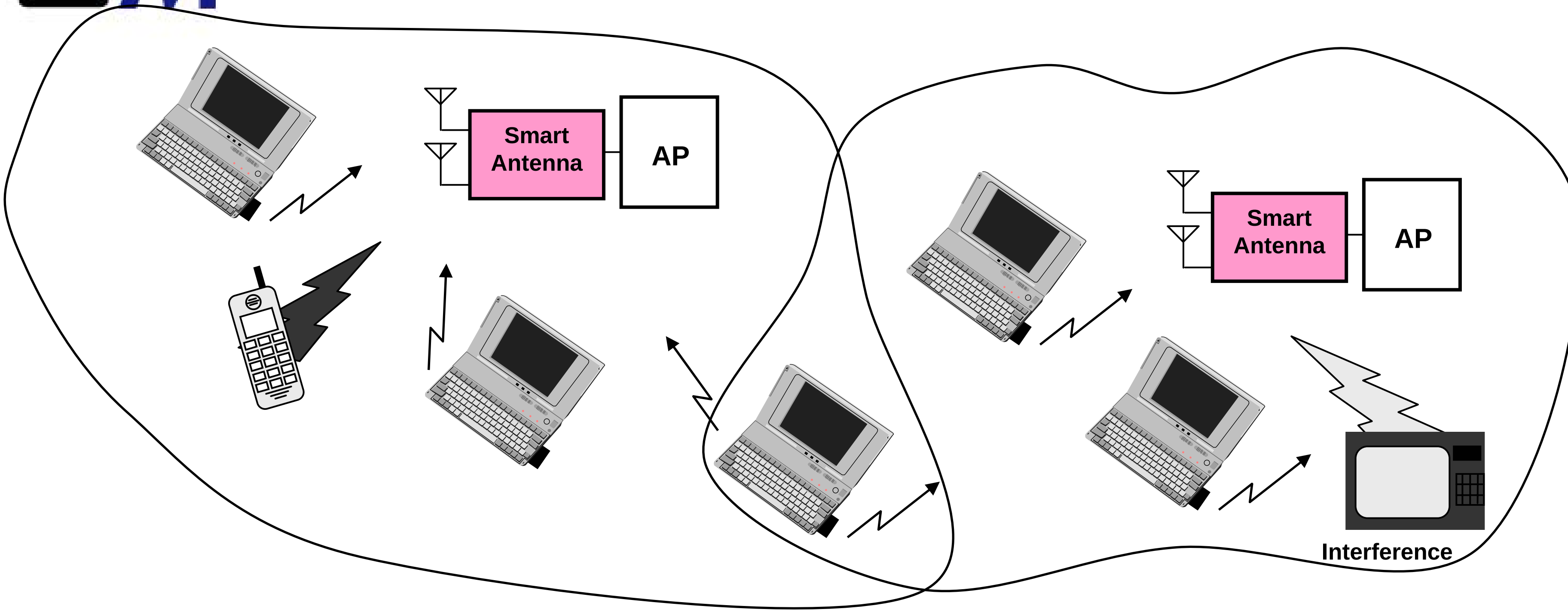
User data rates (Mbps):

	BPSK	QPSK	QAM16	QAM64
R=1/2	6	12	24	
R=2/3				48
R=3/4	9	18	36	54

* optional

Wireless System Enhancements

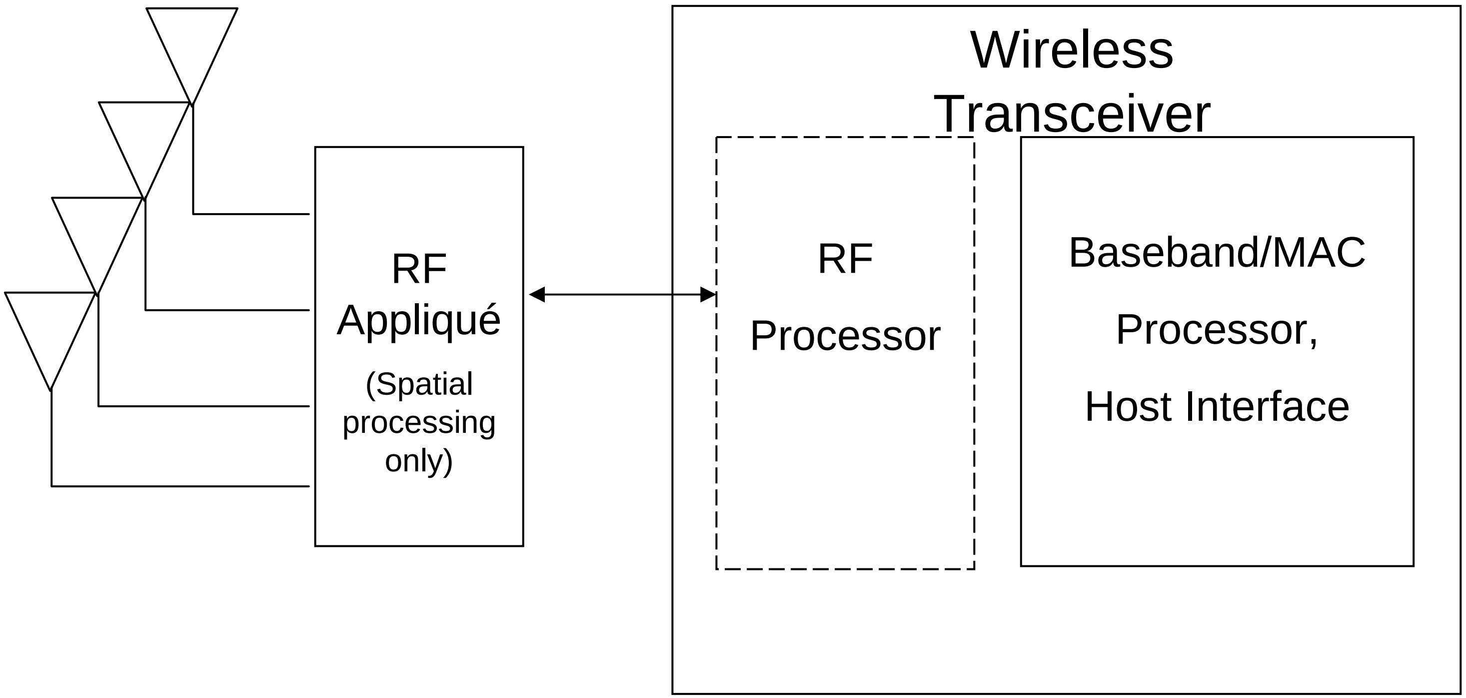




Smart Antennas can significantly improve the performance of WLANs

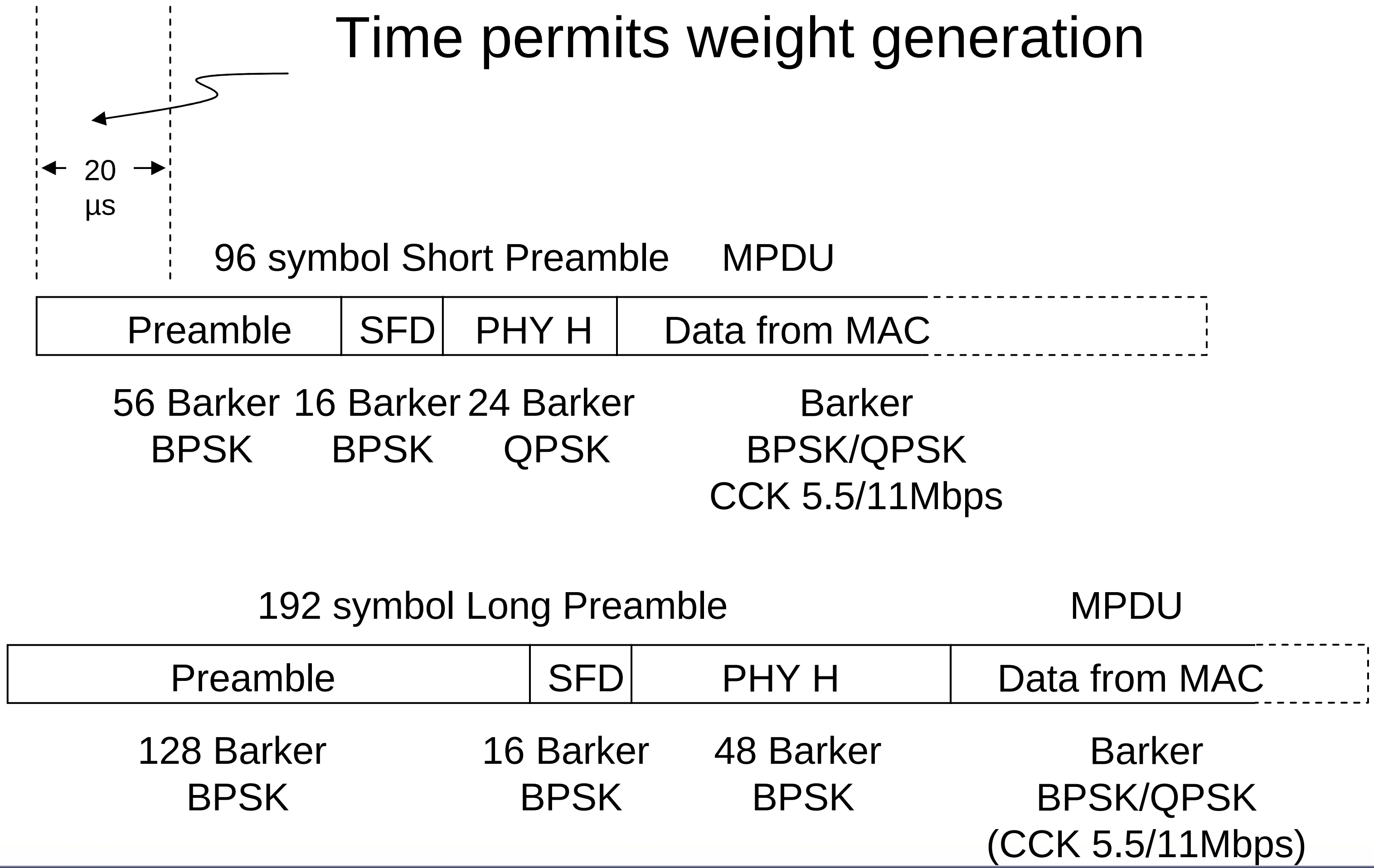
- TDD operation (only need smart antenna at access point or terminal for performance improvement in both directions)
- Interference suppression ⇒ Improve system capacity and throughput
  - Supports aggressive frequency re-use for higher spectrum efficiency, robustness in the ISM band (microwave ovens, outdoor lights)
- Higher antenna gain ⇒ Extend range (outdoor coverage) and lower cost (gain limits)
- Multipath diversity gain ⇒ Improve reliability
- MIMO (multiple antennas at AP and laptop) ⇒ Increase data rates

Appliqué



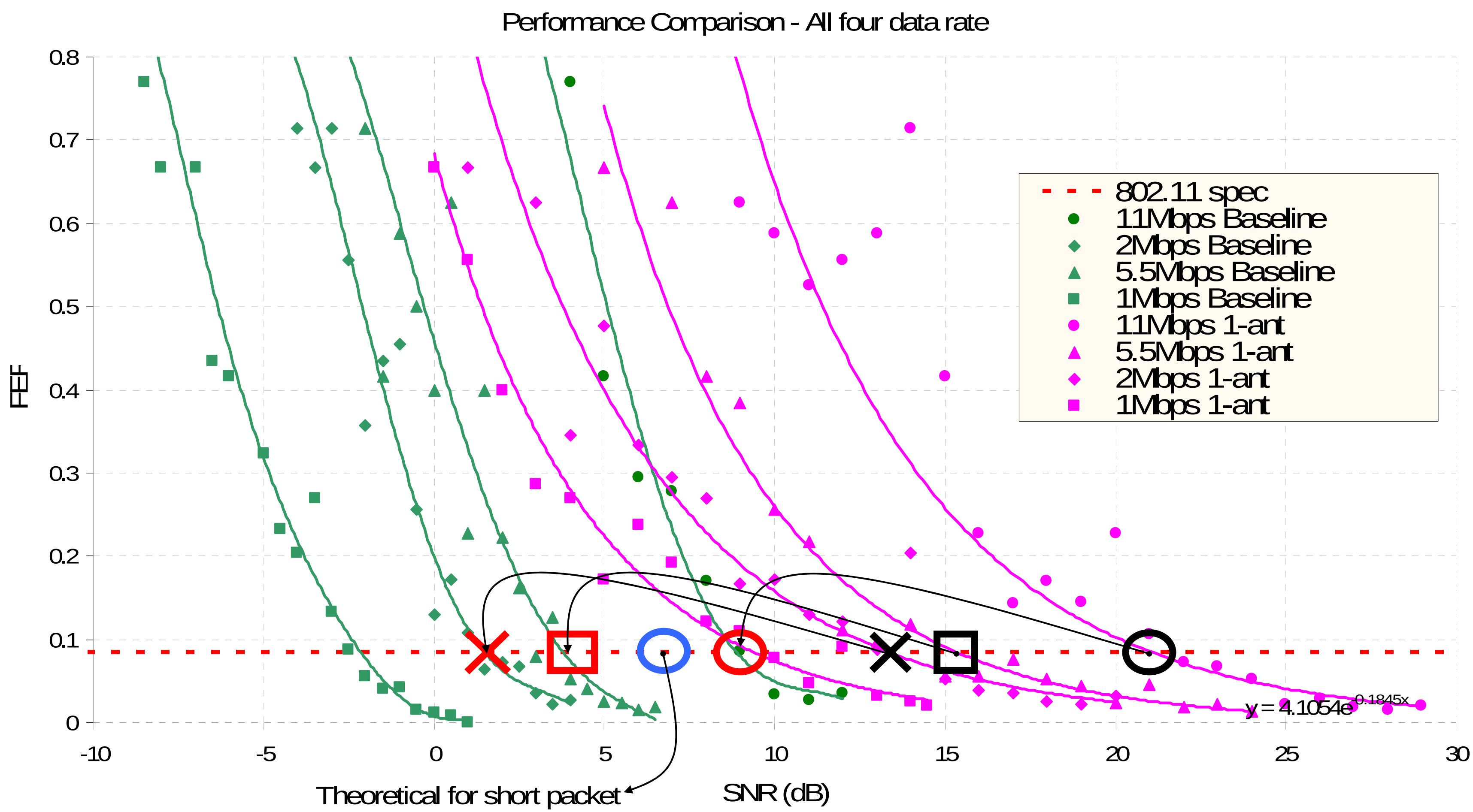
RF
Appliqué
(Spatial
processing
only)
Wireless
Transceiver
RF
Processor
Baseband/MAC
Processor,
Host Interface

802.11b Packet Structure



802.11b Performance with Fading

Achieves a 12 to 14 dB gain over a single antenna



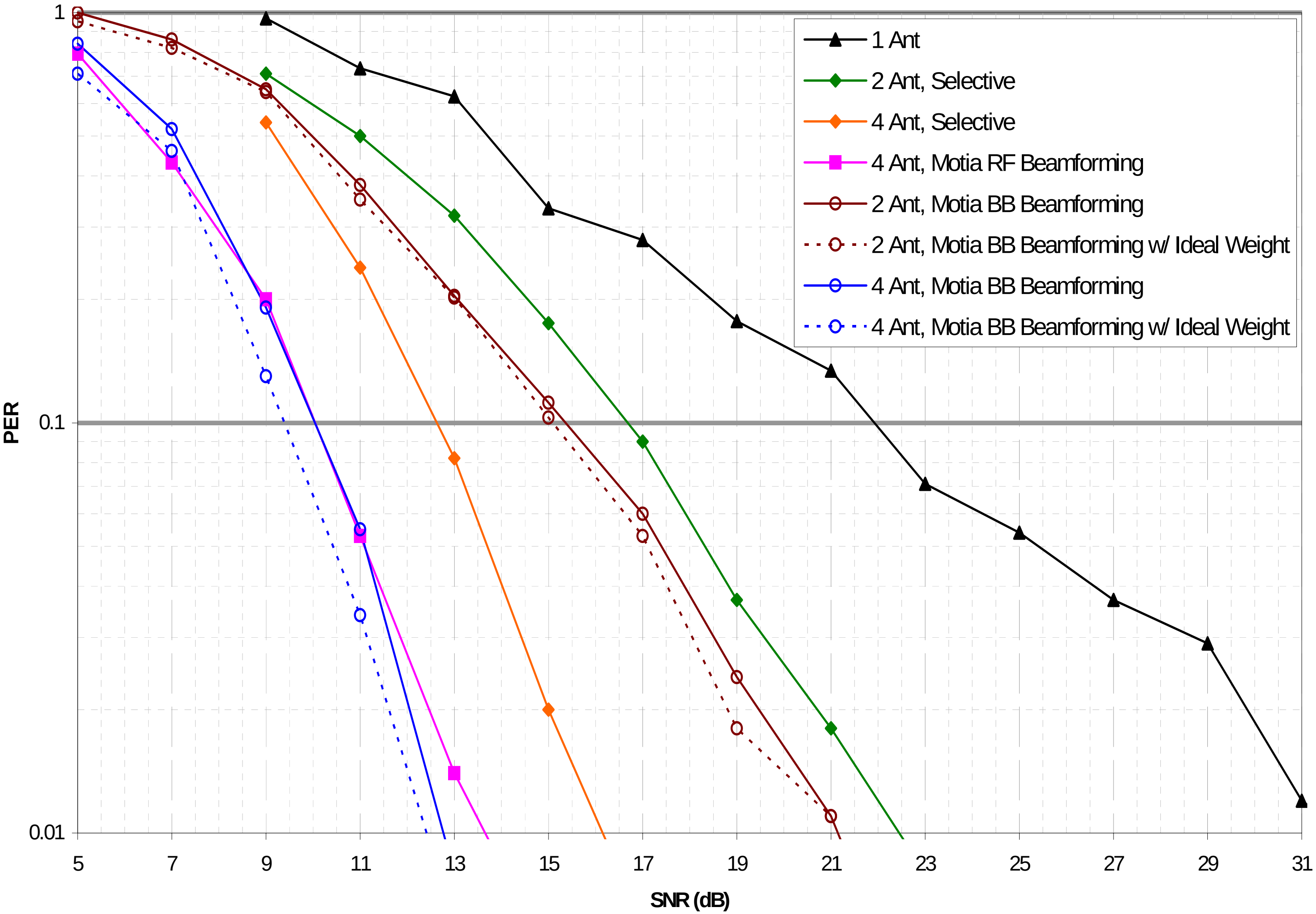
Performance Gain over a Single Antenna in a Rayleigh Fading Channel

2 Antenna Selection	Adaptive One Side	Adaptive Both Sides	Theoretical Bound Both Sides
6.1 dB	12.8 dB	18.0 dB	22.2 dB

2X to 3X Range + Uniform Coverage

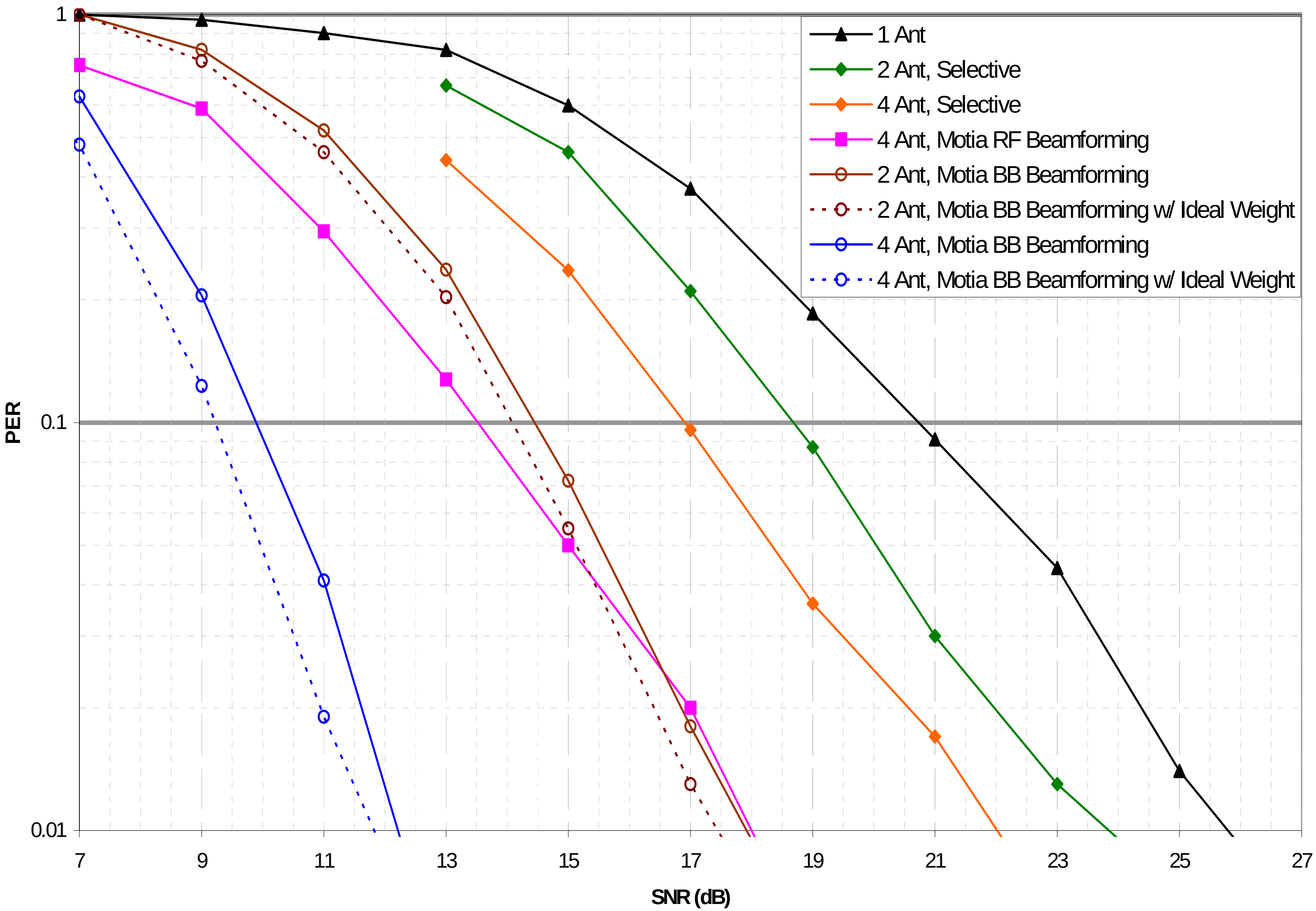
3X to 4X Range + Uniform Coverage

802.11a/g
Flat Rayleigh Fading
24Mbps, Short Packet



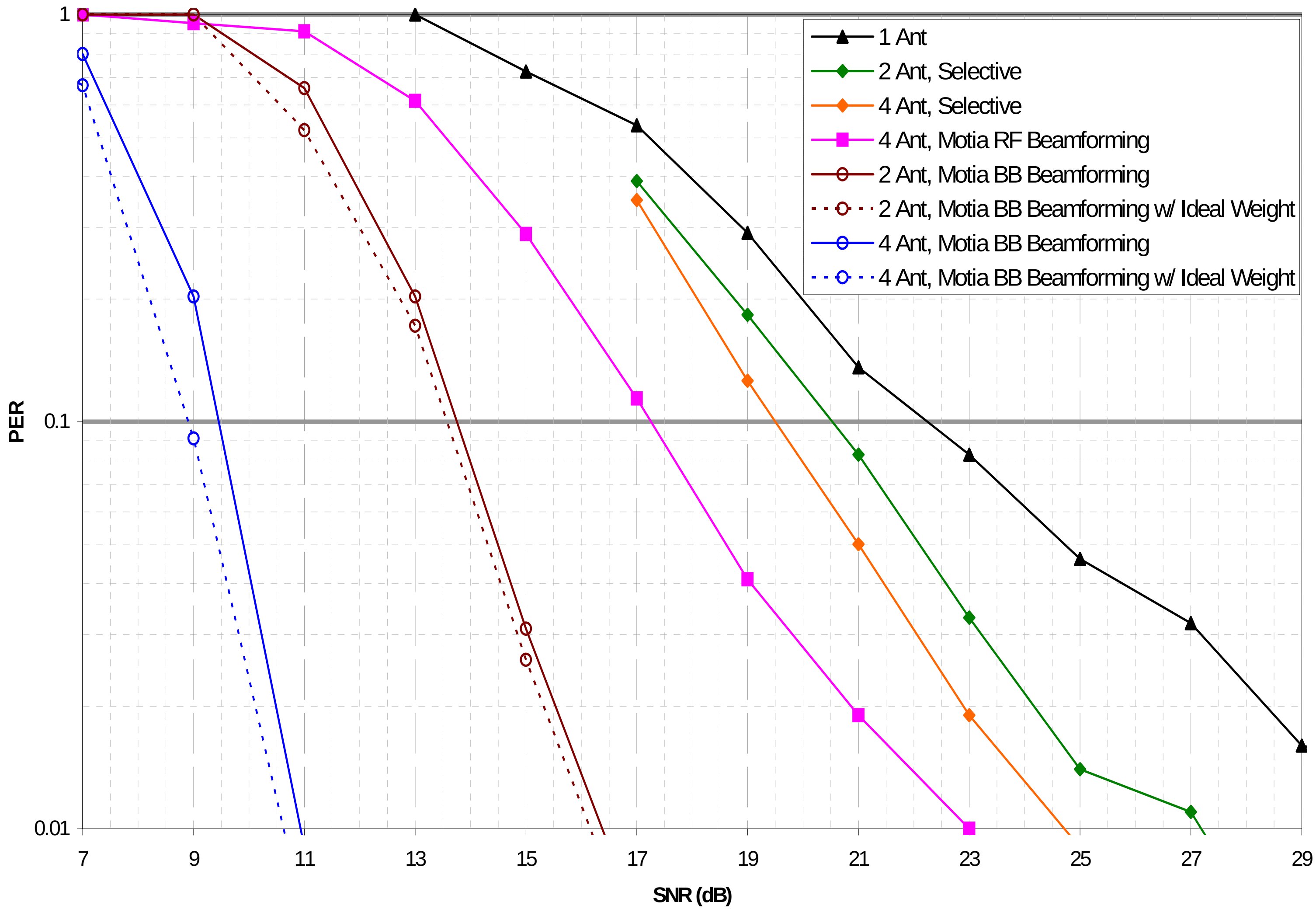
8 symbols/packet

802.11a/g
50ns Exp Decay Rayleigh Fading
24Mbps, Short Packet



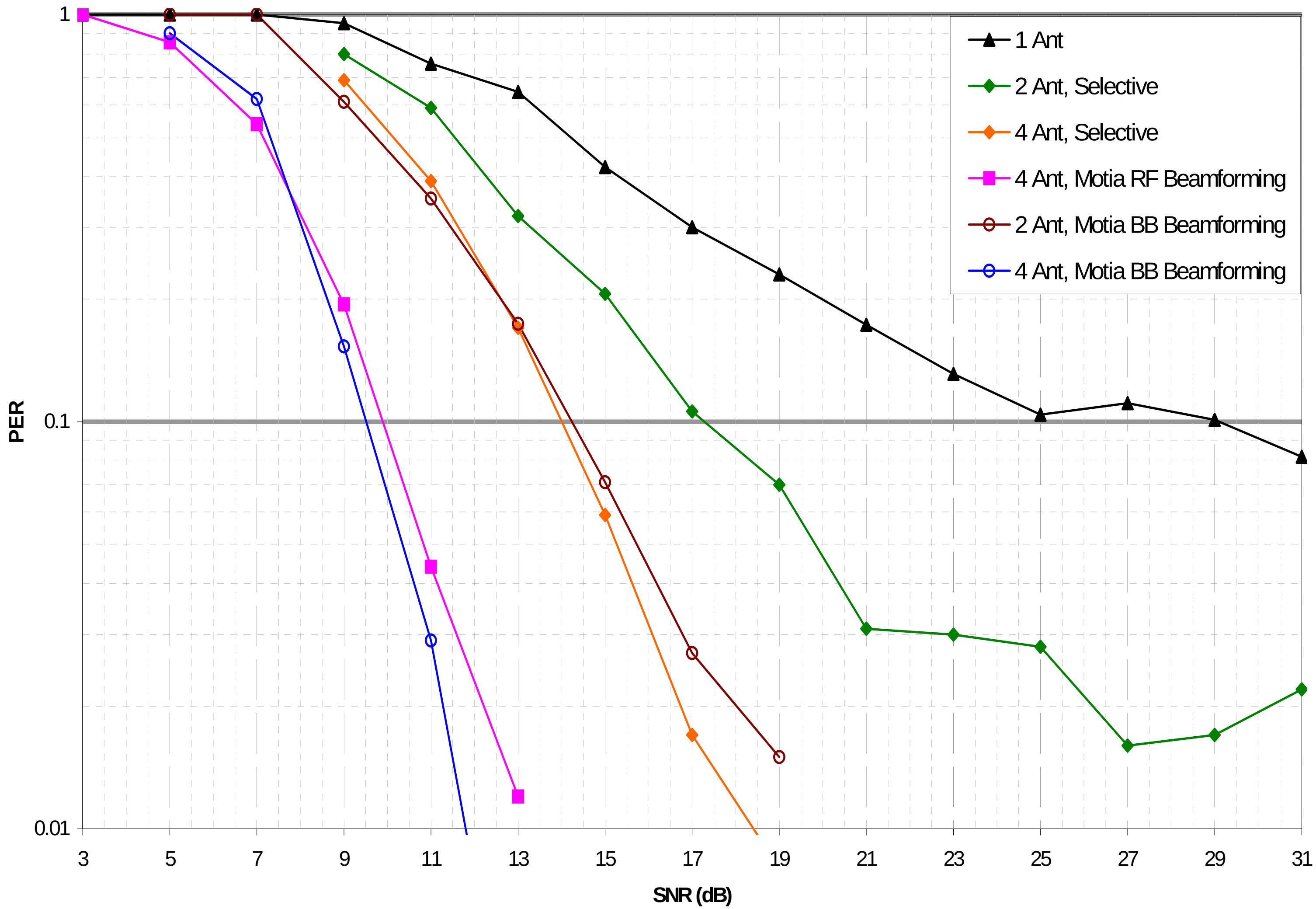
8 symbols/packet

802.11a/g
200ns Exp Decay Rayleigh Fading
24Mbps, Short Packet



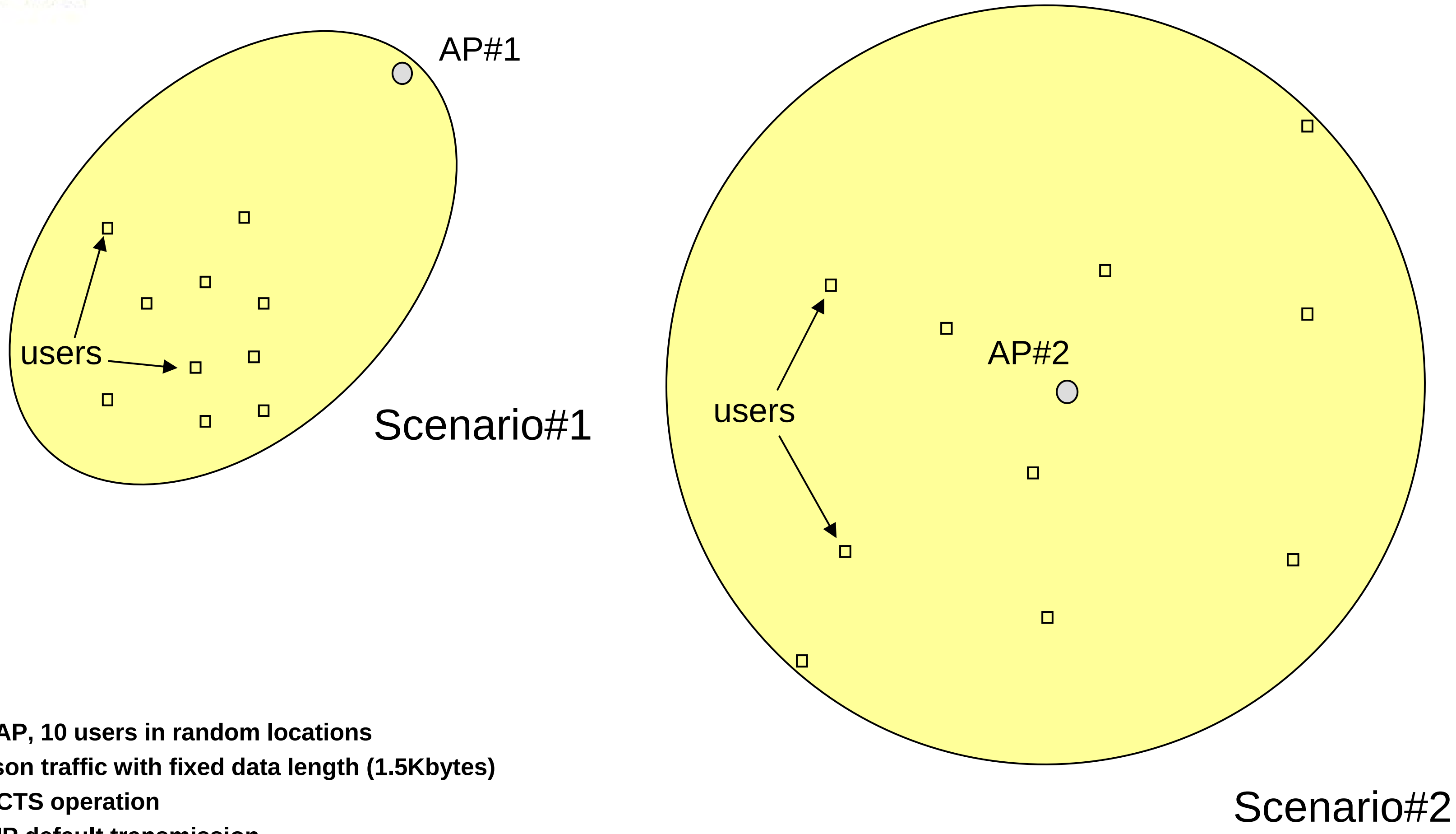
8 symbols/packet

802.11a/g
SUI-2 Channel Model
24Mbps, Short Packet



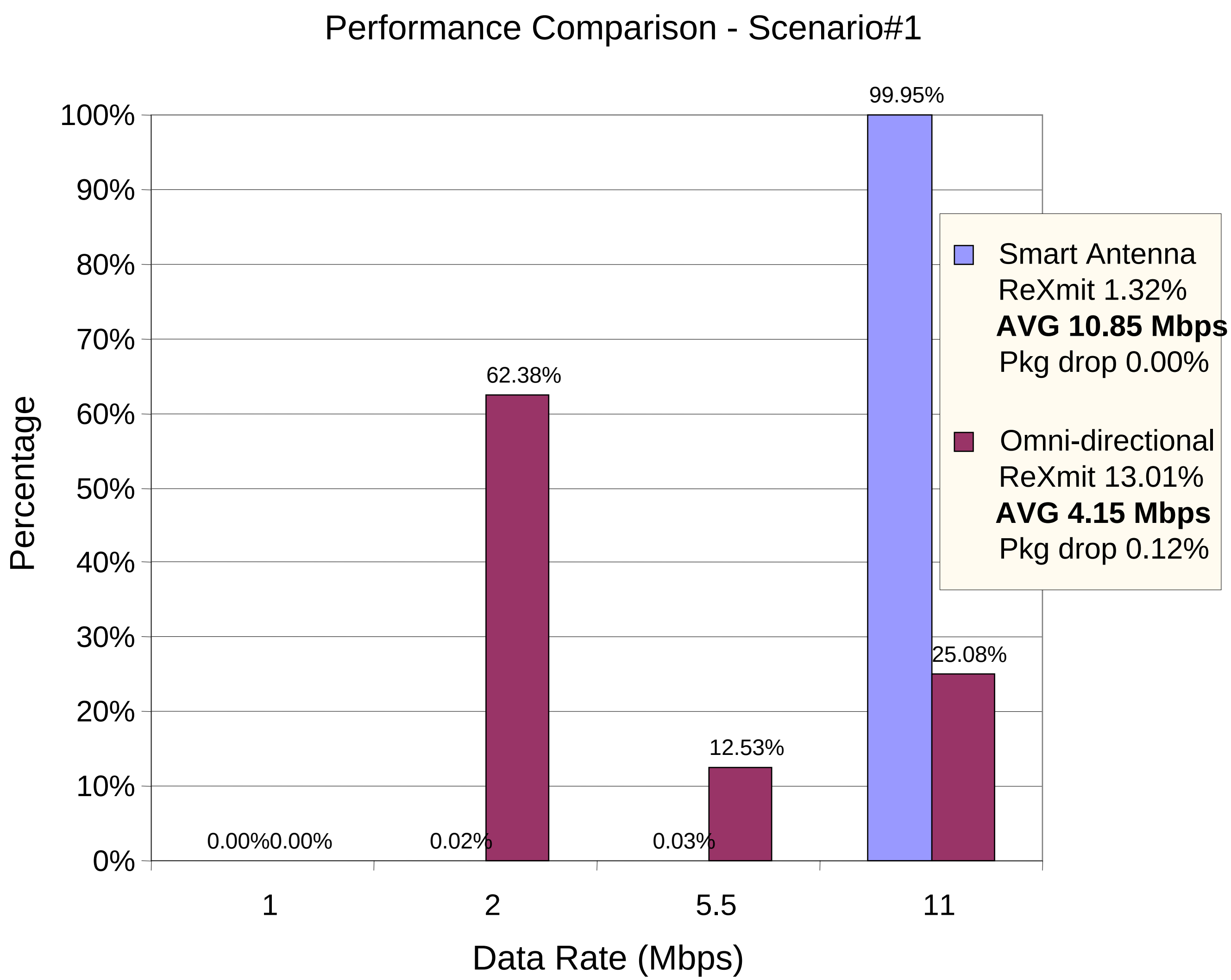
8 symbols/packet

Network Simulation Assumptions

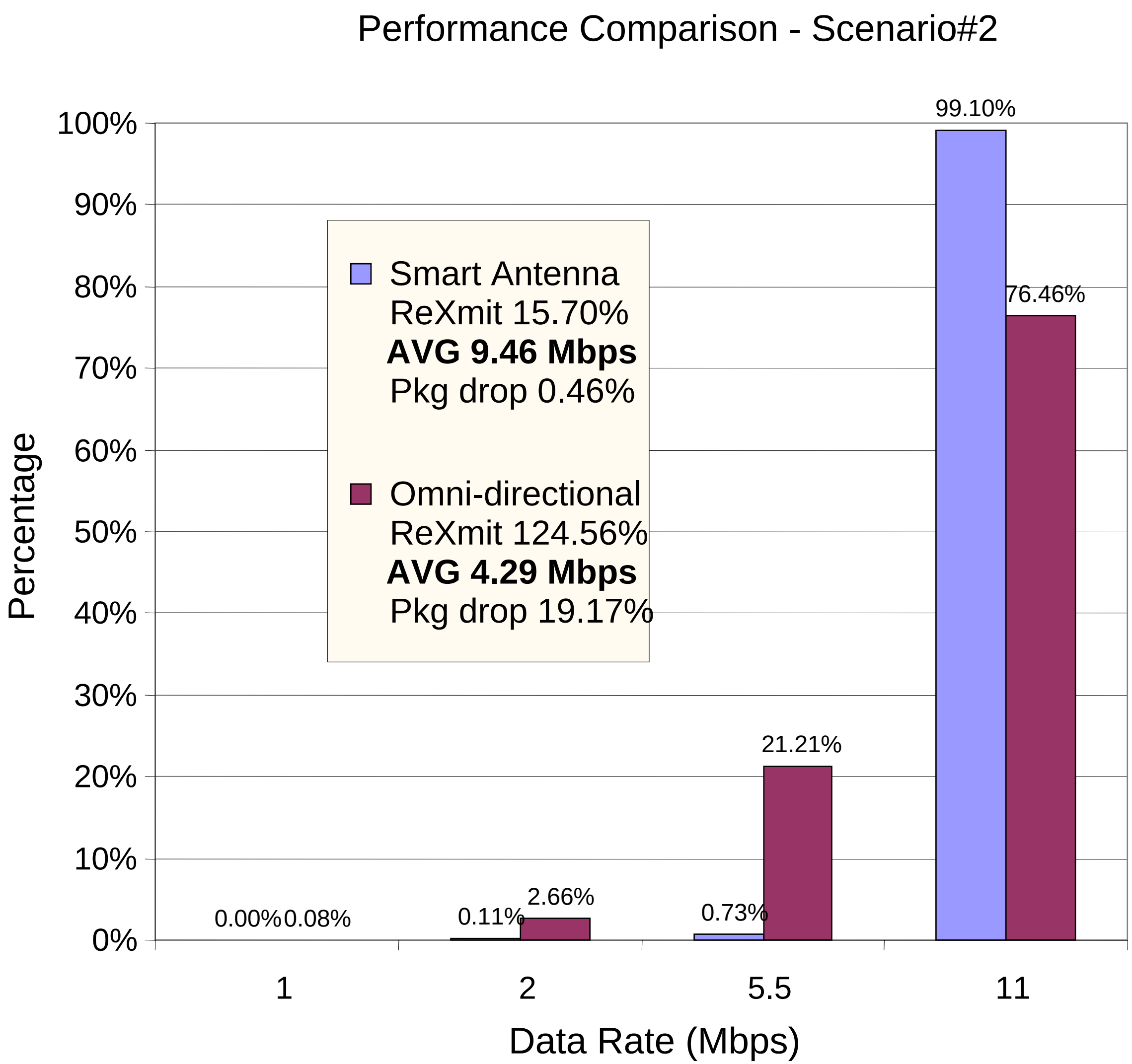


- One AP, 10 users in random locations
- Poisson traffic with fixed data length (1.5Kbytes)
- RTS/CTS operation
- TCP/IP default transmission
- Smart antenna used at AP only

Network Simulation Results



Network Simulation Results



Smart Antennas

- **Adaptive MIMO**
  - **Adapt among:**
    - **antenna gain for range extension**
    - **interference suppression for capacity (with frequency reuse)**
    - **MIMO for data rate increase**
- **With 4 antennas at access point and terminal, in 802.11a have the potential to provide up to 216 Mbps in 20 MHz bandwidth within the standard (802.11n)**

Motia

"We don't believe in dumb access points," says William Rossi, vice president and general manager for Cisco's wireless business unit. "The access points will eventually become smart antennas."

Network World 06/02/03

Communications Design Conference:

- **Craig Barratt (Atheros) - expects the technology (smart antennas) to first appear before the end of next year in silicon for access points supporting multiple antennas linking to single-antenna PC chip sets to provide greater range or capacity - followed by support for multiple antennas on both client and access-point chip sets. (Airgo - MIMO)**

- **Craig Mathias (Farpoint Group) - expects to see cellphones with WiFi emerge at the Consumer Electronics Show in January and to be in production by June - we will see the logical convergence of cellular and WiFi networks next year**

Progression

- Smart antennas for 802.11 APs/clients
- Cellphones, PDAs, laptops with integrated WLAN/cellular
- Smart antennas for both WLANs and cellular in these devices
- MIMO in WLANs (802.11n), with MIMO in cellular (base stations)
- Seamless roaming with WLANs/cellular (WiMAX, 802.20)

Motia

Ultralow Profile Mobile Satellite

Motia

Mobile DBS Limitation

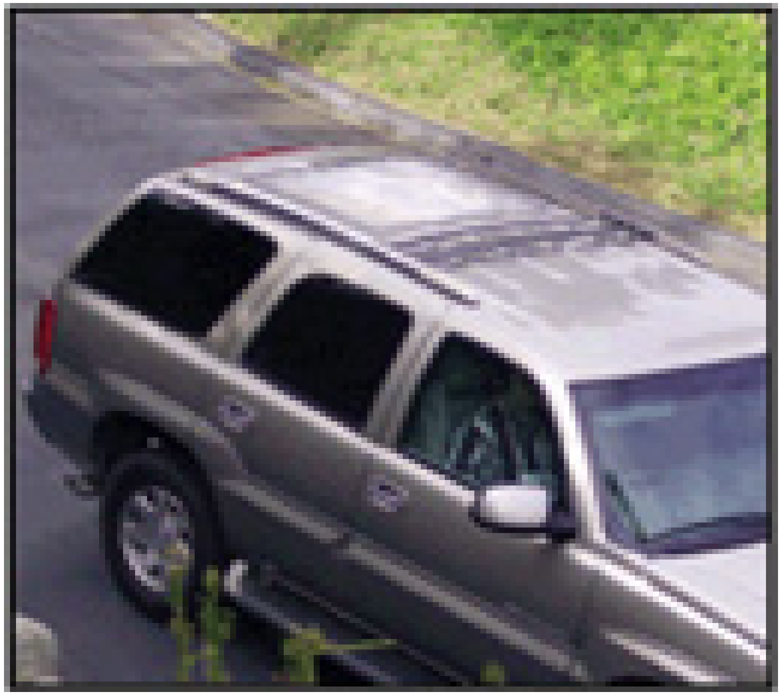
Legacy Products Too Large and Bulky for Minivan/SUV Market

Hybrid Beam Steering Approach

- **Electronic Beam Steering in Elevation Direction**
- **Mechanical Beam Steering in Azimuth Direction**
  - **Most Cost Effective Approach**
  - **Achieve the Lowest Profile**

Motia

Aftermarket



OEM

Low Profile at a Low Cost

Conclusions

- Smart antennas can improve user experience and system capacity by *reducing interference, extending range, increasing data rates,* and *improving quality*
- Smart antennas can be implemented in the physical layer with little or no impact on standards
- Expertise and experience in the development and deployment of smart antennas for cellular can be applied to develop smart antennas for WLANs, and many other wireless applications