UT ECE

Wireless Networking and Communications Group

Wireless Broadband with 802.16/WiMax: Current Performance and Future Potential

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Goals and outline of this talk

- Overview developments in 802.16
- Overview MIMO-OFDM
- Introduce our approach
- Results on 802.16 system performance with and without performance enhancements
- Areas for future study and enhancement

The 802.16 Standard

- Developed for Wireless Metropolitan Area Network (WirelessMAN™)
- A mobile and quick-deployable alternative to current cable access network, e.g., fiber, coaxial and DSL for broadband wireless access
- In many ways, an outgrowth of 802.11
  - PHY is quite similar (OFDM, adapt. Mod, etc)
  - MAC is very different (TDMA, not contention based)
- 802.16a and 802.16d for fixed users, 802.16e for mobile subscribers
- 802.16e = 4G?

Alphabet Soup

- 802.16a: The original version, released Jan. 2003.
  - Three versions: SC, OFDM, OFDMA
  - 2-11 GHz spectrum range
  - Focus on fixed broadband wireless
- 802.16d: The “current” version, released June 2004.
  - Also known as 802.16-2004, very similar to 802.16a
  - Various performance enhancement features in the uplink
  - Provide support for indoor CPE
- 802.16e: The “new” version, released Any Day Now
  - Based on OFDMA concept
  - Supports Mobility
  - Modest performance enhancements expected

802.16: All things to all people

- WiMax: an industrial forum on the 802.16 system
- WiMax releases "profiles" specifying
  - Frequency band
    - Licensed: 2.5-2.69 GHz, and 3.4-3.6 GHz
    - Unlicensed: 5.725-5.850 GHz
  - PHY layer (which of the 10^{∞} options to use)
  - MAC layer (ditto)
  - Other important compatibility issues and testing
  - Specifying higher protocol layers
- Exact performance under various parameters needs careful investigation

Our Objectives

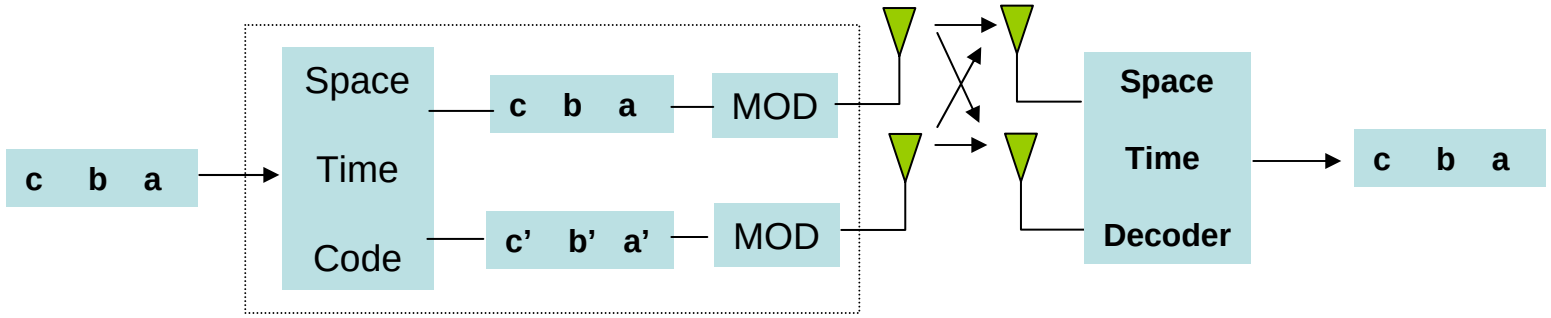
- Develop a strong understanding of *realistic* current 802.16 performance capabilities
  - Highly accurate MAC and PHY simulation
  - Realistic modeling
  - Choice of appropriate 802.16 parameters
- Research and develop techniques to improve the performance
  - Tx Diversity (part of our baseline system)
  - Spatial Multiplexing (MIMO), and associated techniques
  - HARQ
  - Multiuser OFDM
  - Interference Cancellation

Overview of MIMO

- Multiple-Input Multiple-Output (MIMO) has many benefits
- Spectral Efficiency
  - Multiple data streams can be simultaneously transmitted, i.e. *Spatial Multiplexing (SM)*
  - SM increases throughput dramatically
- Link Quality
  - Wireless link SINR fluctuates due to fading and interference
  - MIMO can provide many quasi-independent channels
- Coverage
  - Increase coverage area due to diversity
- Cost (?)
  - More efficient use of spectrum, support multiple users
  - Reduced power requirements
- **There is a fundamental tradeoff between SM and diversity**

Spatial Diversity

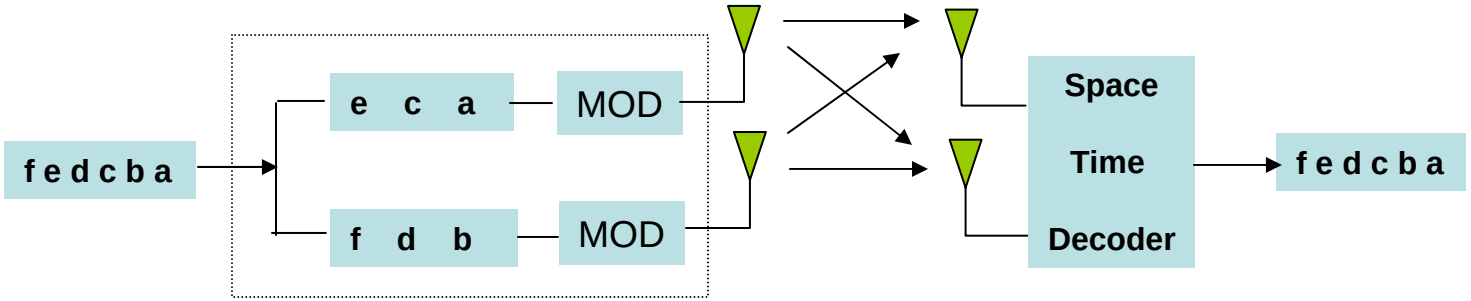
- Transmit Diversity
  - Space-time Code (STC): Redundant data sent over time and space domains (antennas)
  - Receive SNR increases about linearly with diversity order $N_r N_t$
  - Provide diversity gain to combat fading
  - Optional in 802.16d (2x2 Alamouti STBC), used in 3G CDMA



- Capacity (max data rate): $C = \log(1 + \frac{SNR}{N_t}(\sum_{i=1}^{N_t}\sum_{j=1}^{N_r}|h_{i,j}|^2))$

Spatial Multiplexing

- MIMO Multiplexing
  - Data is *not* redundant – less diversity but less repetition
  - Provides multiplexing gain to increase data-rate
  - Low (no) diversity compared with STC
  - Not available in current standard.



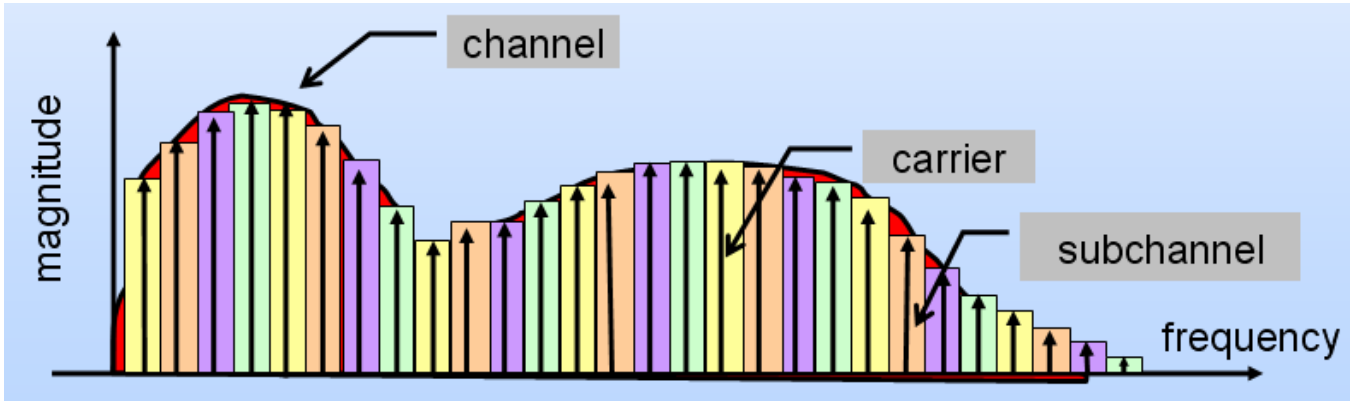
- Capacity: $C_{MIMO} = \log\det(\mathbf{I} + \frac{SNR}{N_t}(\mathbf{H}'\mathbf{H}))$
  $\simeq min(N_t, N_r)C_{SISO}$

MIMO Precoding

- Spatial multiplexing
  - Low diversity
  - Error performance is very poor in low SNR regime
- Solution: Space-time Precoding
  - # transmit antennas > # data streams
  - Intelligently allocate bits & power over transmit antennas
  - Extra antennas provide some diversity
  - Precoder can be designed for single-carrier, or multi-carrier system with carrier cooperation

Overview of OFDM

- OFDM: Orthogonal frequency division multiplexing
  - Divide the wideband channel into many subcarriers
  - Each subcarrier experiences flat fading
  - Inter-symbol interference (ISI) is mitigated
  - Robustness again frequency-selective fading
- Other advantages
  - Frequency diversity
  - Smart resource allocation among subcarriers is possible



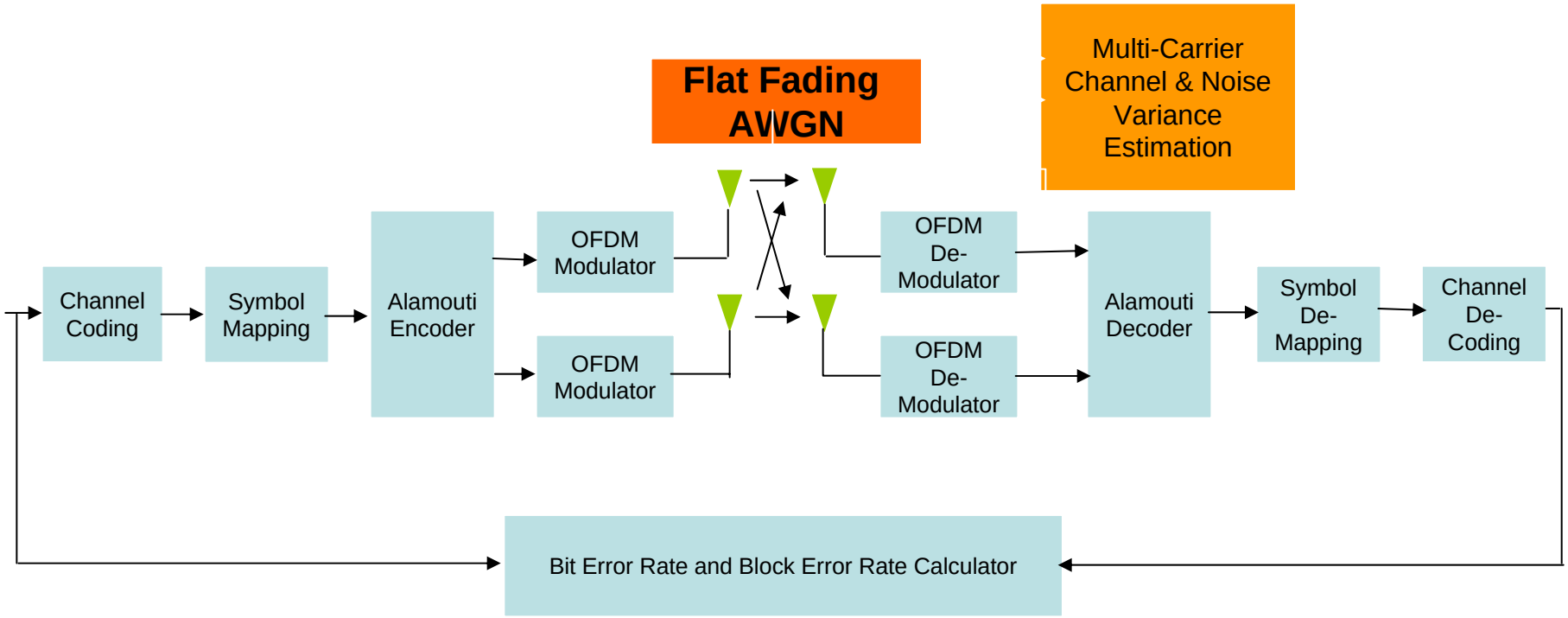
OFDM and MIMO are natural partners

- MIMO provides high data rates, but spatial interference
- OFDM provides parallel narrowband channels that are straightforward to use
- The penalty for not using OFDM with MIMO is the need for interference cancellation in both the time and spatial domains at the receiver
- Most nontrivial proposed MIMO systems include OFDM implicitly or explicitly

Link Level Simulations

- Link level simulations characterize the performance of individual 802.16 links under different conditions
  - Multipath and scattering characteristics of the wideband wireless channel (delay spread, angular spread, and Doppler spread)
  - Average signal to interference plus noise ratio (SINR)
  - Performed for each rate mode from BPSK R1/2 to 64QAM R3/4
- Instantaneous BER and BLER are collected as a function of instantaneous SNR (measure on a per MAC PDU basis)
- Average bit error rate and block error rate are computed as a function of average SINR (Averaged over the instantaneous measurements)

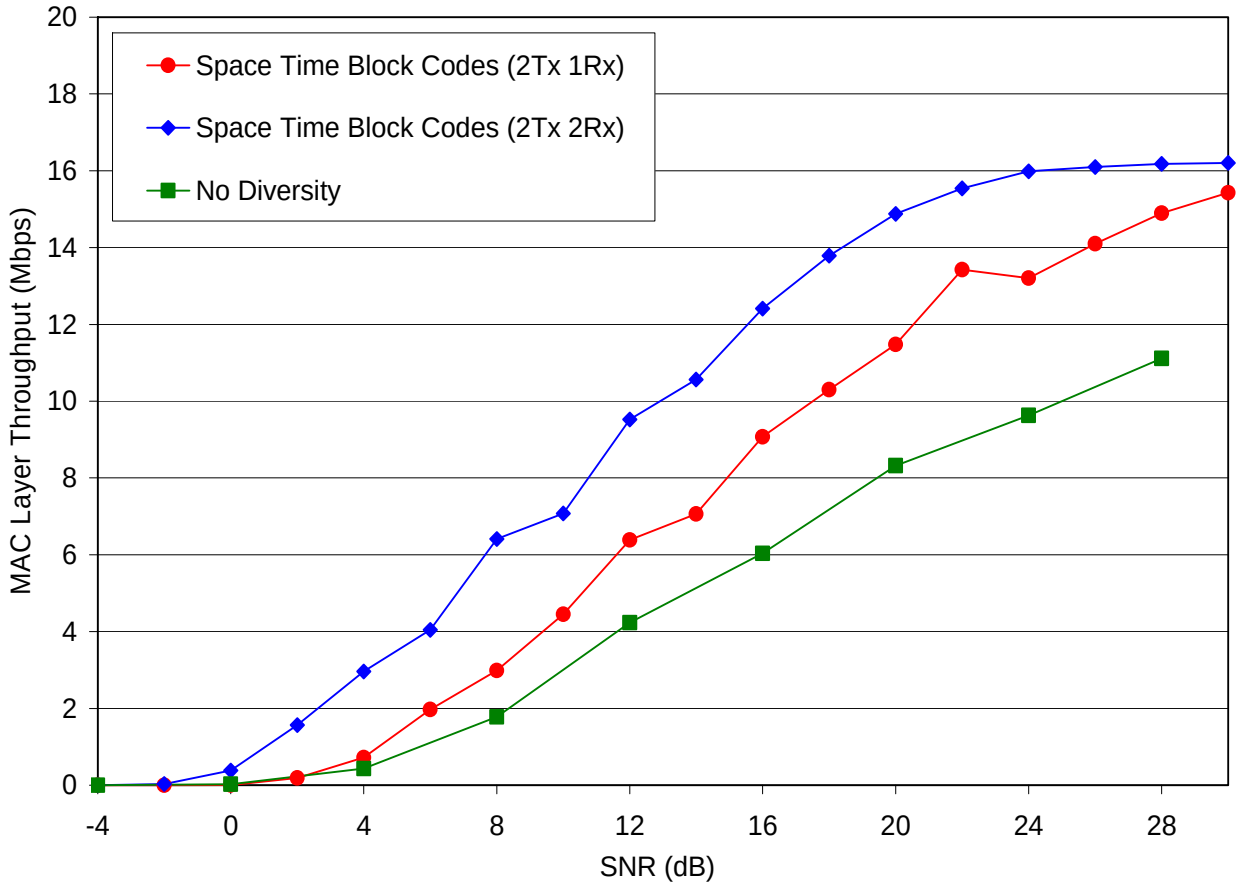
Link Level Simulation – STBC



Wireless Channel Model

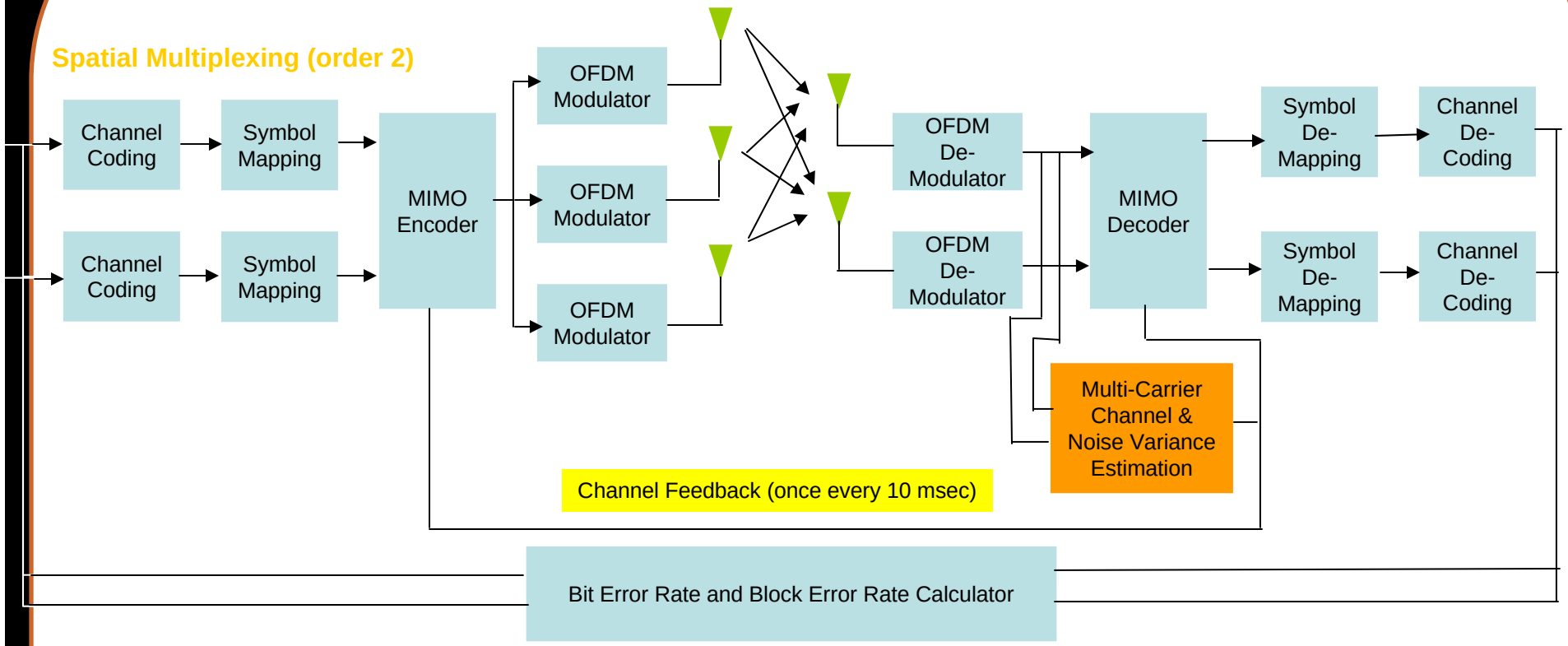
- The MIMO channel model is based on the 3GPP specifications (TS 25.996).
  - # of paths (distinct delay) = 6
  - # of sub-paths = 20 per path
  - Model the spatial correlation (multiple Tx and Rx antenna)
    - angle of arrival (per cluster or path)
    - angle of departure (per cluster or path)
    - angular spread (per cluster or path)
    - antenna element spacing (Tx and Rx)
    - carrier frequency
  - Models the temporal correlation based on:
    - Velocity of Tx
    - Velocity of Rx
    - carrier frequency
  - Interference is modeled as faded white Gaussian noise

DL Throughput for 5 MHz Channel Bandwidth



These results incorporate link adaptation. For each value of SNR simulation is performed for each of the 7 modes and the optimum mode is selected such that throughput is maximized

MIMO Extensions for 802.16



Required new preamble structures. In the downlink still 2 OFDM symbols were used in the beginning of each frame for preambles. The preambles were used for frequency synchronization and channel estimation

MIMO Extensions (closed loop)

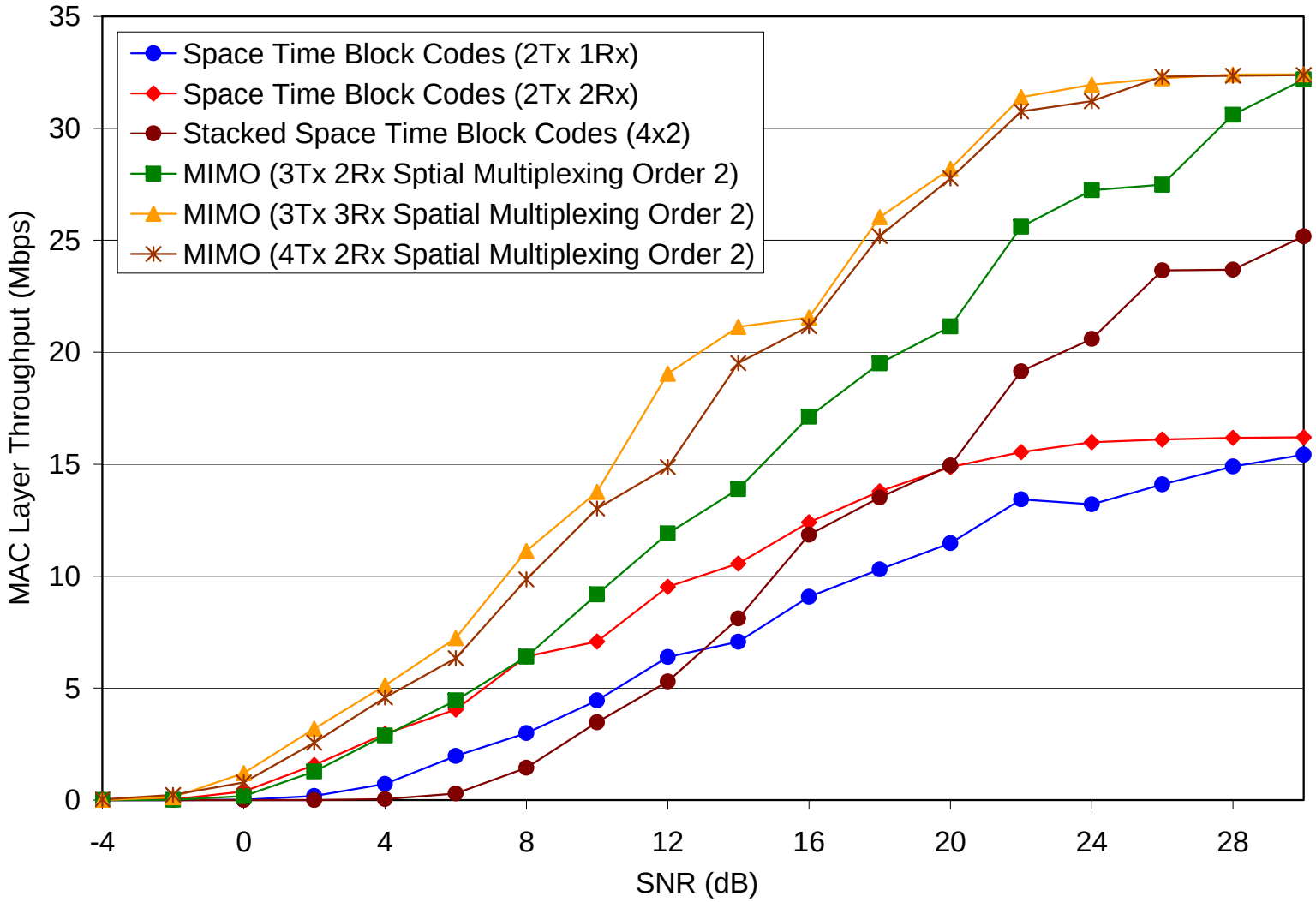
- MIMO systems can be generalized broadly under two categories:
  - Closed loop: CSI (channel state information) is used at the transmitter to perform pre-coding or transmit optimization
  - Open loop: CSI is *not* used by the transmitter (e.g. BLAST or STBC for diversity)
- Without any feedback or diversity, a simple 2x2 MIMO system performed very poorly at low to medium SNR (4–12 dB)
- Solution: **Space-time precoding** provides compromise between SM and diversity

MIMO Extensions: Precoding

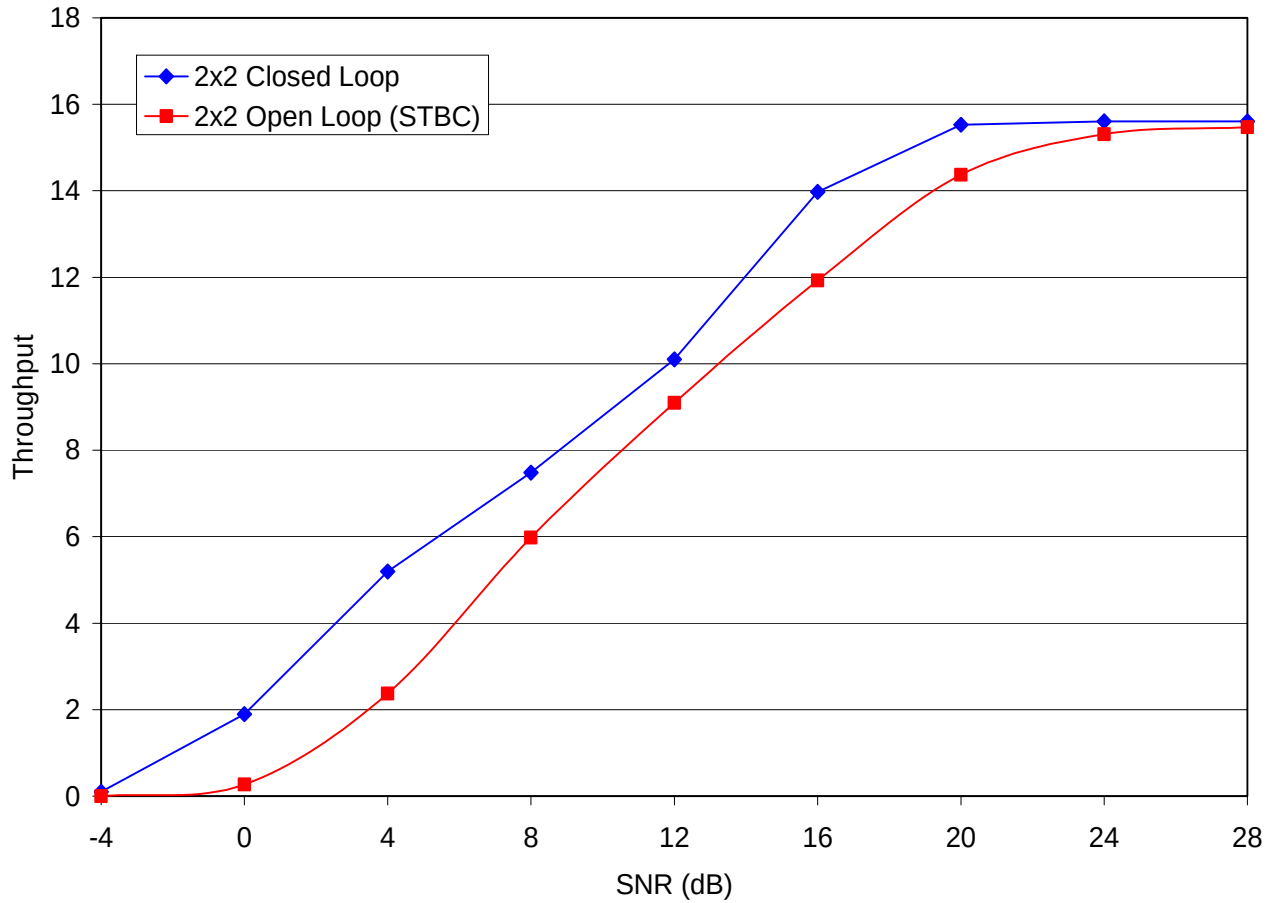
- The CSI is used by the transmitter and the receiver to generate a pair of pre-coding and decoding matrices based on certain criteria
  - Maximize signal to noise ratio in each sub-carrier
  - Minimize mean square error of the detected symbol
  - Achieve user fairness in terms of rate, errors, etc.

- In an FDD system this requires a feedback channel (5 – 40 kbps, assuming low mobility)
  - Performance benefit due to feedback is significant: 2 – 4 dB depending on conditions.

DL Throughput for 5 MHz Channel Bandwidth



Advantages of Closed loop (cont)



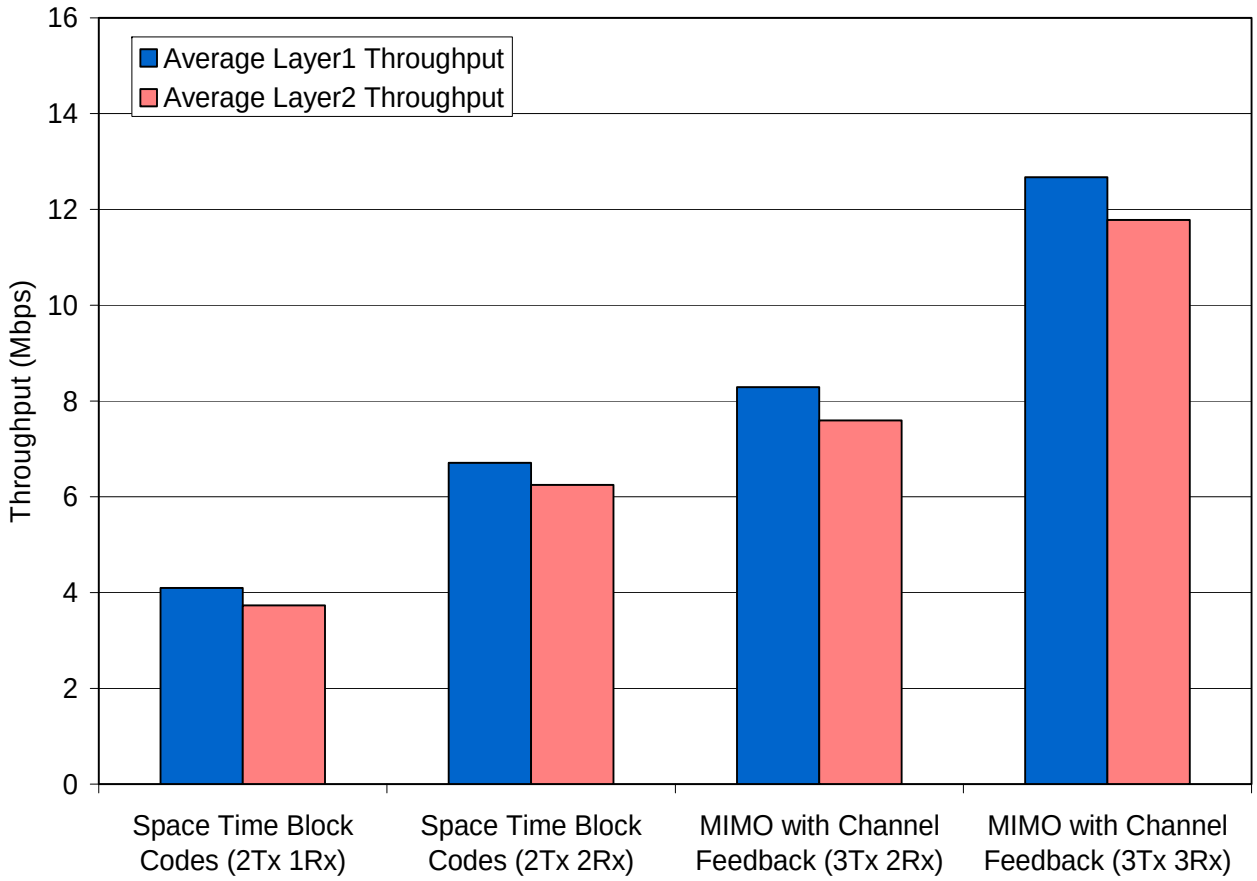
Both results for a single data stream – closed loop system is able to do precoding

System Level Modeling

- Link level simulation only characterized the performance of an 802.16 link under different conditions
- A multi-cellular deployment requires system level modeling
- Static Simulation:
  - Two tiers of interference considered
  - The SNR at any given location is determined by the Tx power of the serving and interfering cells and their respective path losses
  - Power control can be integrated if desired
- Dynamic Simulation:
  - A true MAC/RLC simulation that uses the Link Level (PHY) mapping tables.
  - Models all components of the MAC and RLC such as fragmentation and concatenation of MAC SDUs to MAC PDUs, scheduling, ARQ, etc.

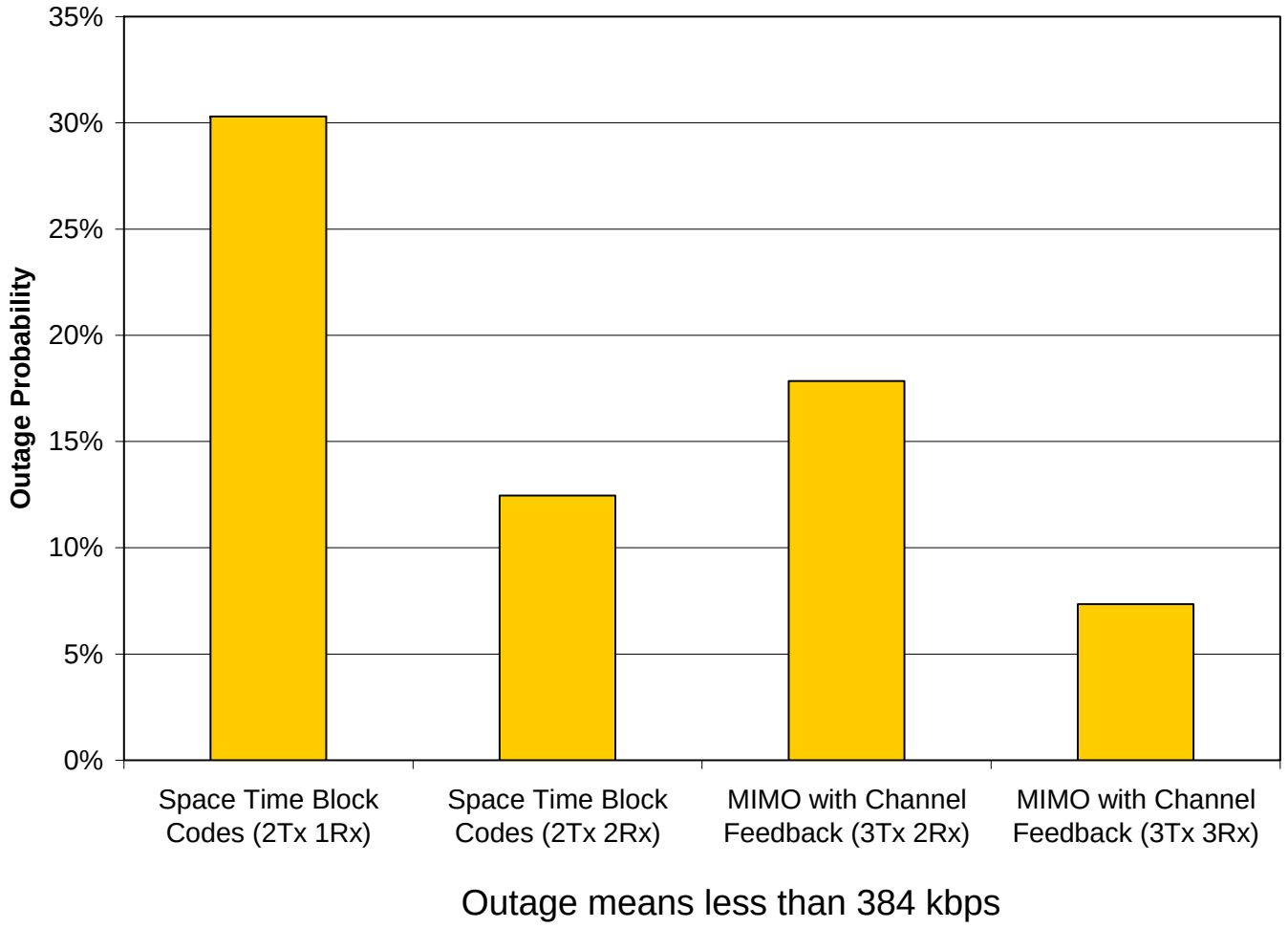
MIMO really does increase data rate!

(also, WiMax has a darn good MAC)

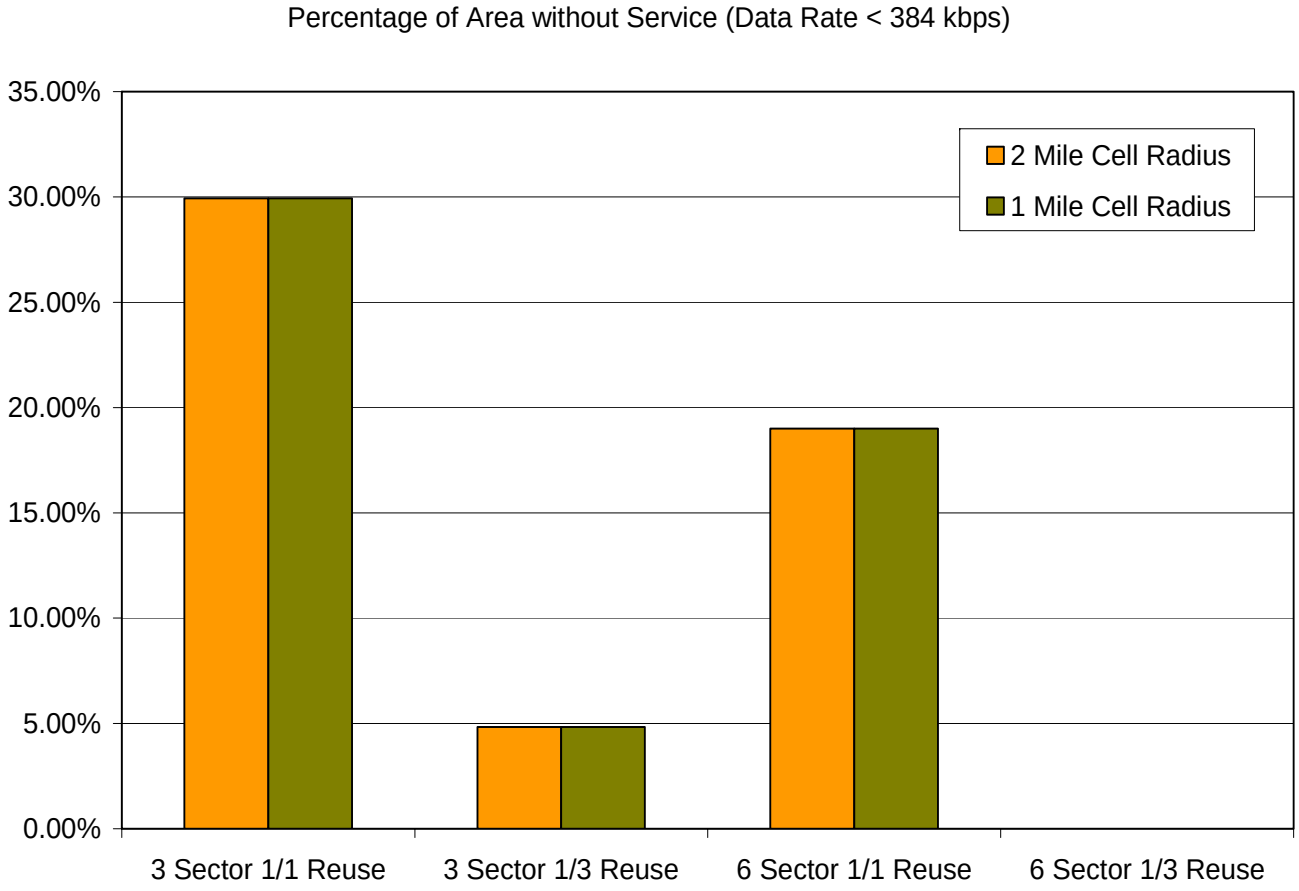


6 sector sites with 1/1 frequency reuse and 2 mile cell radius

Precoding helps diversity



Low-data rate users are heavily interference-limited



Results are for a 2x1 STBC system

Further Work- Cellular MIMO

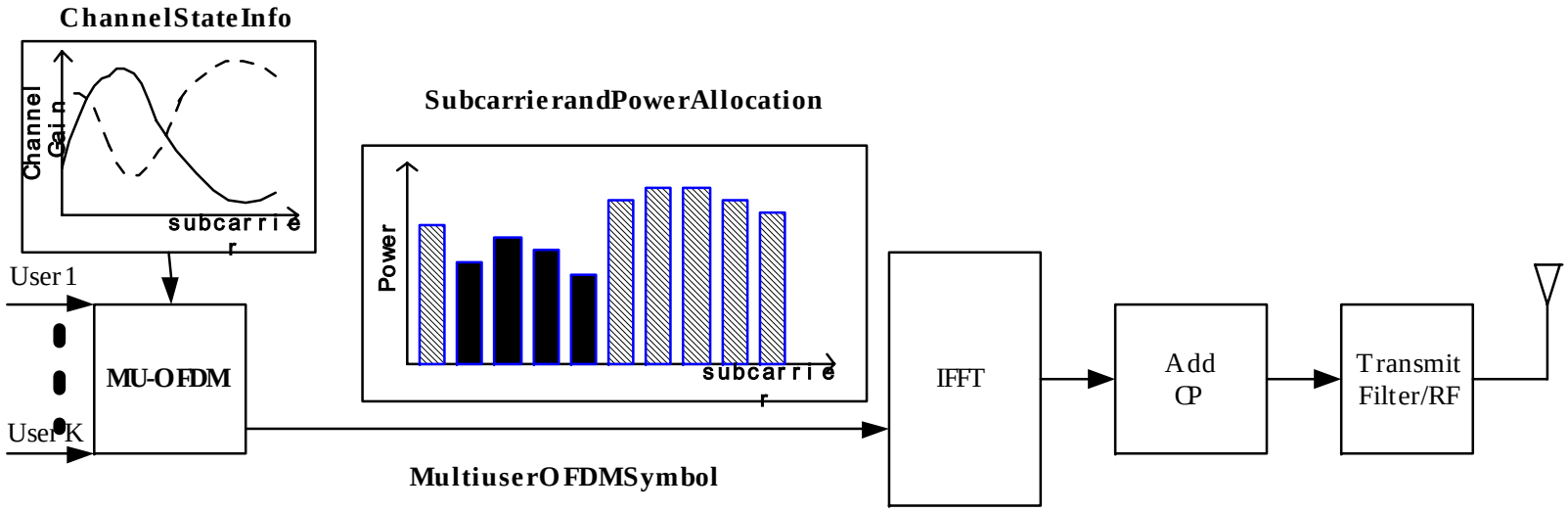
- Most previous research on MIMO has been for a noise limited (single cell) scenario.
- As we have seen here, with high levels of other-cell interference (low SINR), spatial multiplexing doesn't work very well
- In fact, as SINR decreases, it's often better for spectral efficiency to send a single stream of data! (Blum *et al*, Dai *et al*, Catreux *et al*, Choi and Andrews)

Ongoing Research: MIMO Interference Reduction Techniques

- Distributed antenna MIMO systems
  - Connect distributed antennas by fiberoptic or wireless backhaul
- Cooperative scheduling amongst base stations
  - Like “smart” frequency/spatial reuse
- Cellular MIMO power control to maximize net utility
  - Instead of inverting channels to get equal SINR, jointly maximize throughput and minimize transmit power

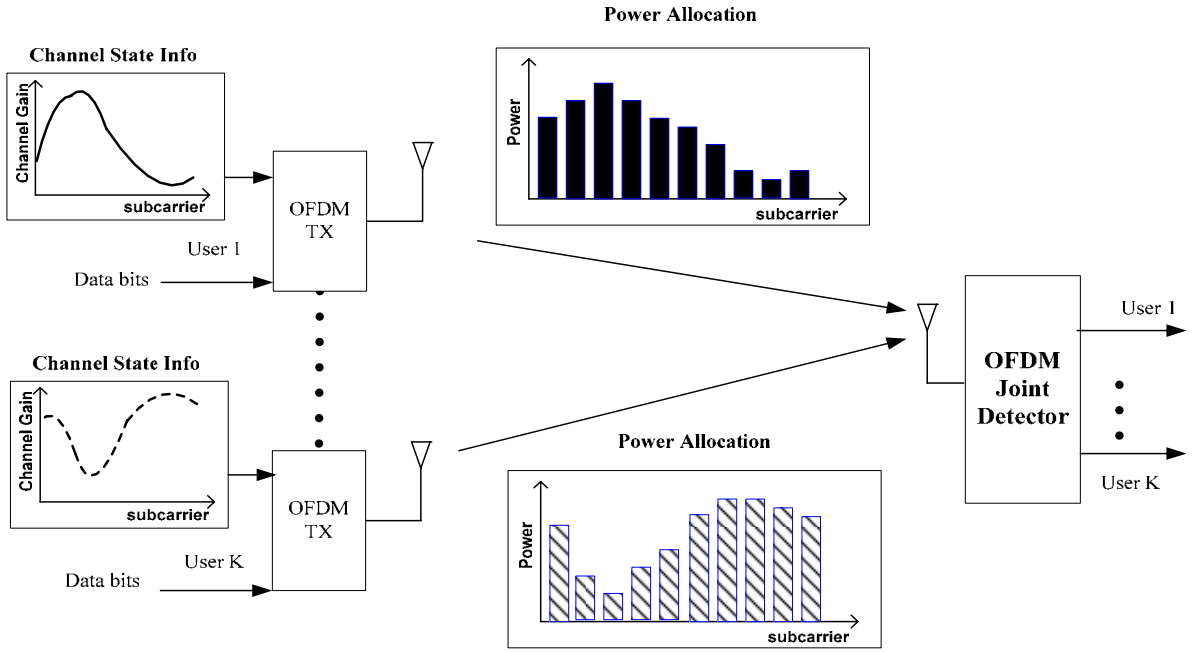
Further Work – Multiuser OFDM

- Different subcarriers are allocated to different users, according to channel conditions
- Gains are from 50%-200% relative to TDMA based OFDM
- Practical implementation in the 802.16 context is interesting, exists in simple form in 802.16e



Further Work – Interference Cancellation for MIMO-OFDM

- When multiple 802.16 networks co-exist, interference from adjacent cells is a major performance impairment
- Developing an OFDM Rx with IC is highly desirable
- Similar in scope and spirit to the "SAIC/MAIC" work ongoing at SBC Labs, but multicarrier makes it harder



Conclusions

- 802.16/WiMax is the beginning of a good wireless broadband standard
  - Based on reasonably cutting edge technology
  - Very flexible, should prove evolvable and scalable
- But don't believe the hype
  - Spectral efficiencies/data rates still obey the laws of physics and information theory, esp. at finite power and cost
  - An incremental increase in throughput and coverage over 1xEV-DO/HSDPA
- Do get truly impressive rates, a suite of improvements needed
  - MIMO, and required technologies to support MIMO
  - Advanced Signal Processing (Interference cancellation, etc)
  - ARQ, Adaptive Multiuser OFDM, Power Control

More Information

- This talk has been posted to my web page "publications":

  http://www.ece.utexas.edu/~jandrews/

  (Can also Google "Jeff Andrews")
- See *IEEE Communications Magazine* article, on the same page, of the same title
- Related technical articles, also on the same page, and list of references on next 2 slides
- E-mail: jandrews@ece.utexas.edu

  Please be patient, though ☺

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