Development of MIMO and Space-Time Coding

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Outline

- Introduction
- Development of MIMO
- Development of Space-Time Coding
- Conclusions

Background (circa 1980)

Multipath is an impairment only, that must be avoided or mitigated:

- **Multipath fading (fading margin needed)**
- **Delay spread (limits data rate)**
- **Angular spread (limits sectorization)**

Interference: w/o multipath, M-element adaptive array can null M-1 interferers if they are outside main beam

Mobile radio textbook: Adaptive arrays are not effective against multipath interference as too many reflected signals to null

Development of MIMO – 1980's

1984: MMSE combining for interference suppression in multipath [1] – key concept:

$$w = \alpha R_{nn}^{-1} u_d^*$$

- **With multipath, multiple paths result in phase and amplitude for each transmitted signal at each antenna element – same technique for interference suppression as in LoS, but:**
  - **With M-element array, can null N<M interferers, with same performance as M-N antennas w/o interferers**
  - **Can null interferers as long as independent fading – antenna separation of ¼ λ**

Development of MIMO – 1980's

1987: Extension to interference suppression [3]

- **Interference can be other desired signals**
  - **Other users for one base station for increased system capacity (MU-MIMO – note term MIMO not used until mid 1990's)**
  - **Other antennas on base station/terminals if fading on antennas independent (MIMO)**
- **Capacity formulas developed for both CSI known and unknown at Tx – eigenanalysis w and w/o waterfilling (based on extension of [2])**
- **Limitations:**
  - **Narrowband**
  - **Medium SNR results only**
  - **Linear (MMSE) combining or MLD**

MIMO [3]

Fig. 6. Radio system consisting of two users, one with M antennas and the other with N antennas.

MIMO [3]

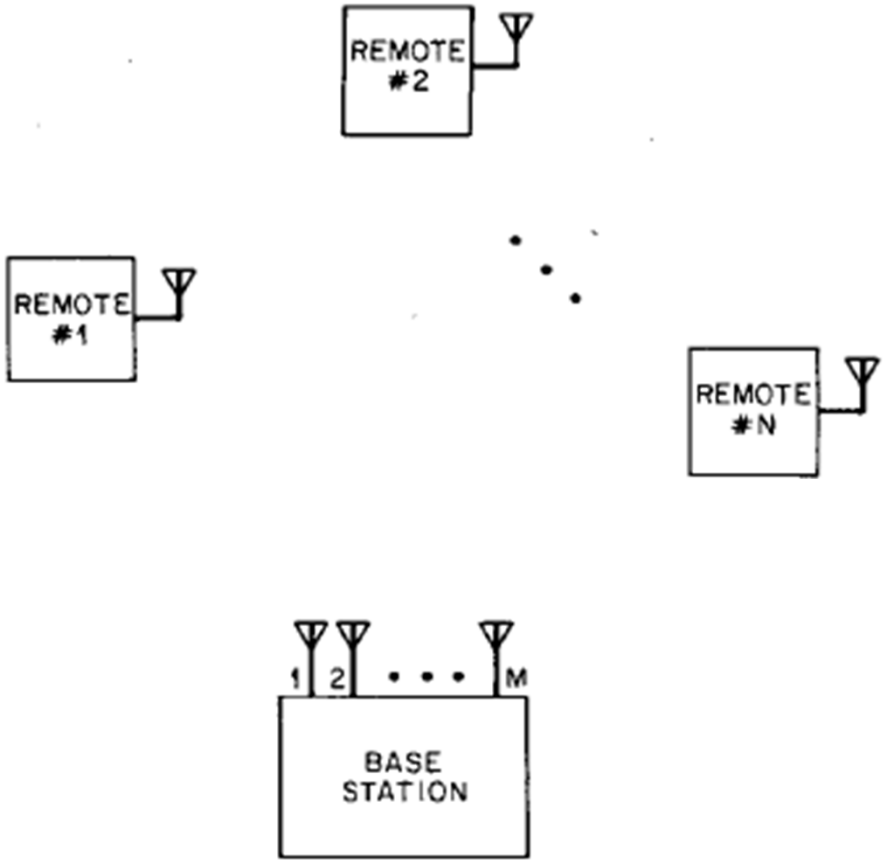

Fig. 1. Radio system consisting of a base station with M antennas and N remotes, each with one antenna.

MIMO [3]

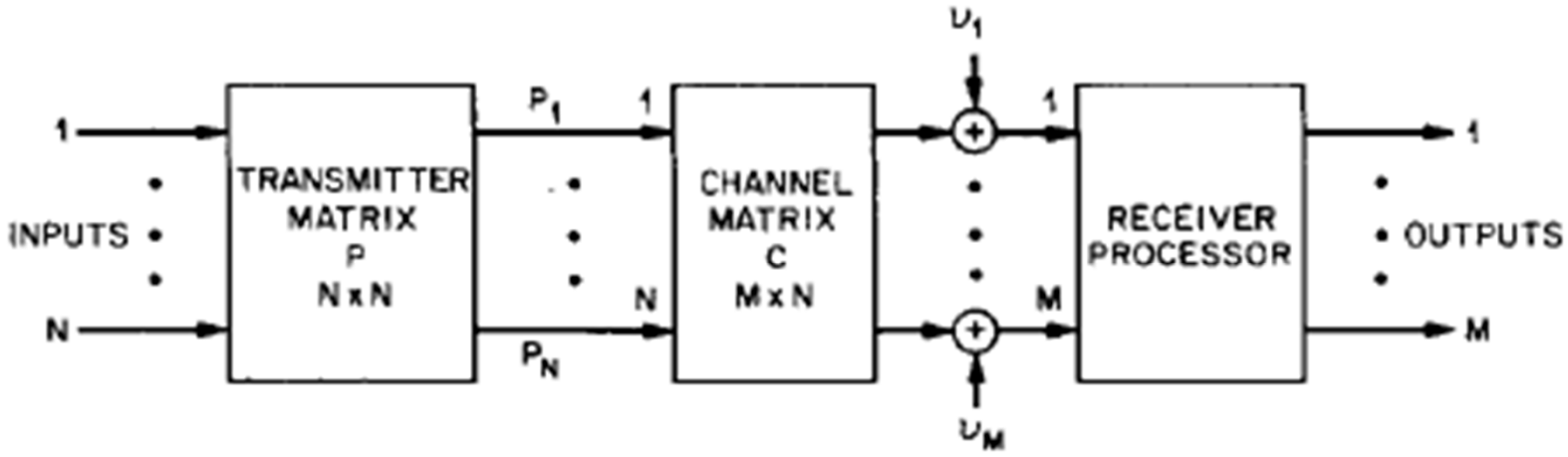

Fig. 2. System represented in matrix form.

$$I_s = \sum_{i=1}^{N} \log_2 (1 + \rho \lambda_i P_i)$$

The P_i's that maximize I_s can be found by using the water fill analogy [14], i.e.,

Development of MIMO - Limitations

Narrowband:

- **Too computationally complex for MIMO with equalization**
- **OFDM developed around the same time – seen as potentially solution, but overall too complex at the time**
- **Application: Wireless PBX (cordless phone network)**
  - **First step: Developed an 8X8 MIMO testbed using a fading simulator – 64 DSP's with complex Gaussian noise multiplication**
  - **Demonstrated 8-fold spatial multiplexing (paper at CISS'91)**

Development of MIMO – 1990's

Further research at AT&T discouraged:

- **Need for wireless PBX with MIMO not seen (customers not asking for this)**
- **In cellular, 2-4% annual growth predicted (conversion to digital provided 3-fold increase - met near-term need)**

- **1990's: Research at Stanford University on SM and OFDM, including startups for implementation**
- **Bell Labs [4]:**
  - **Asymptotic results for high SNR (M-fold increase in capacity with M Tx and Rx antennas with no increase in SNR)**
  - **Practical implementation that approached capacity limits (ZF with SIC - extended to MMSE with SIC)**

Development of MIMO – 1990's

Not widely deployed in 1990's:

- **Cellular**
  - **Spending on upgrades to next generation with increased DSP, not more antennas**
    - **Interference suppression (MMSE) added to base stations in late 1990's, but with same two Rx antennas**
  - **Key point – in interference limited systems, added antennas best used for interference suppression**
    - **MIMO with SM can provide M-fold increase in user data rate, but to only a few users with only about 20-40% increase in network capacity**

Development of MIMO – 1990's to Today

Not widely deployed in 1990's (cont.):

- **WLANs – not interference limited, but just being developed**

- **2000's:**
  - **Commercial widespread deployment first in WLANs – IEEE802.11n, then IEEE802.11ac**
  - **Cellular deployment (LTE/WiMAX) for higher data rates, but major gains to be achieved with network MIMO/CoMP/etc., i.e., MIMO among base stations.**
  - **Massive MIMO for 1000-fold increase in next decade**

Other Applications of MIMO

The basic concept of MIMO with a channel matrix has been applied to many other areas:

- **Optical fiber communications**
  - **MIMO channel is fiber with multiple modes launched by array of lasers and using array of detectors**
- **Radar:**
  - **Statistical MIMO radar**
    - **Contrast with MIMO in communications**
      - **Wide vs. closely spaced Tx and Rx antennas**
      - **Small scatterer vs. wide scattering environment**

Other Applications of MIMO (cont.)

- **Free-space MIMO**
  - **No multipath – opposite of normal use where multipath is required for SM gain**
  - **Tx array and Rx array are large enough and the arrays are spaced close enough so that in near-field – essentially use spatial multiplexing with separate beams for each Rx antenna**

Development of Space-Time Coding

- **Initial Goal (1990's): Gains of multiple antennas but with only one mobile antenna (multiple base station antennas only)**
  - **Transmit diversity – first techniques:**
    - **Frequency offset between transmit antennas for fast fading – diversity gain with coding**
    - **Time delay between transmit antennas**
      - **Create delay spread – diversity gain at Rx with**
        - **RAKE with CDMA**
        - **Repetition code [5]**
        - **Equalization [5]**

Development of Space-Time Coding (cont.)

- Issues with equalization
  - Complex to implement
    - Linear equalizer may require many taps
    - MLSE – delay spread in the channel further complicates DSP
- Solution (1998)
  - Add complexity at Tx, use simple Rx
    - Space-time code – Alamouti [6]
  - Extended to multiple Tx and Rx antennas [7]
- Deployed in 2000's in WLANs, cellular (LTE/WiMAX)
  - STBC, STTC
  - LTE: STFC

Conclusions

- **MIMO and space-time coding**
  - **Decades in development, with both incremental and breakthrough innovations**
  - **Rapid deployment when need is seen**
  - **Extensions in other areas**
  - **Potential for much further research/improvements**

References

1. J. H. Winters, "Optimum combining in digital mobile radio with cochannel interference," *Special Issue on Mobile Radio Communications IEEE Journal on Selected Areas in Communications*, July 1984, *IEEE Trans. on Vehicular Technology,* August 1984.
2. J. Salz, “Digital transmission over cross-coupled linear channels,” *AT&T Technical Journal*, vol. 64, no. 6, pp. 1147–1159, July–August 1985.
3. J. H. Winters, "On the Capacity of Radio Communication Systems with Diversity in a Rayleigh Fading Environment," *IEEE Journal on Selected Areas in Communications*, June 1987.
4. G. J. Foschini, “Layered space–time architecture for wireless communication in a fading environment when using multiple antennas,” *Bell Labs Syst. Tech. J.,* vol. 1, p. 41–59, Autumn 1996.
5. N. Seshadri and J. H. Winters, "Two Signaling Schemes for Improving the Error Performance of Frequency-Division-Duplex (FDD) Transmission Systems Using Transmitted Antenna Diversity," *VTC’93.*
6. S.M. Alamouti, "A simple transmit diversity technique for wireless communications,” I*EEE Journal on Selected Areas in Communications* 16 (8): 1451–1458, Oct. 1998.
7. Vahid Tarokh, Nambi Seshadri, and A. R. Calderbank, "Space–time codes for high data rate wireless communication: Performance analysis and code construction,” *IEEE Transactions on Information Theory* 44 (2): 744–765, March 1998.