ELG5132: Smart Antennas

- **Prof:** Dr. Sergey Loyka (CBY A608)
- **Lectures:** Mon. 16:00 - 17:20, Wed. 14:30-15:50 (on Teams)
- **Office hours:** You are encouraged to ask questions during and after lectures (but not before). When sending an email, please include the course code ELG5132 in the subject line (otherwise, it will not be answered).
- **Course web page:** http://www.site.uottawa.ca/~sloyka/
- **Prerequisites:** Required background: basic communication theory, signals & systems, probability, linear algebra/matrices. Antennas & propagation is a plus (but not required).
- **Assignments/Quizzes:** informal (bonus points)
- **Course mini-project:** topics will be provided.
- **Final exam:** 3h in December, date TBD, open book

On-line course delivery:

- **Lectures**: via MS Teams; a team has already been set up, you should have access to it (via your uOttawa account) if you are registered for the course. If you are registered but cannot access it, please contact our grad. office for assistance with registration/uOttawa account.
- Please familiarize yourself with MS Teams and practice using it beforehand. Here is useful link, with many other links.
- **Project presentations**: via MS Teams (practice well in advance).
- **Final exam**: via Brightspace (use your uottawa account).
- All announcements, lecture slides and other information will be available on the course web page, found at http://www.site.uottawa.ca/~sloyka/
- If you send me an email and expect an answer, include “ELG5132” in the subject line (no answer otherwise).

- **Marking scheme:**
  - Mini-project report + presentation 50%
  - Final examination 50%
  - Lots of bonus points to everybody who takes active part in the course
- **Calendar Description:** Wireless systems and their limitations. Introduction to propagation and antenna arrays. Concept of smart antenna; spatial processing; space-division multiple access. Types of smart antennas. Range and capacity improvement. Beamforming algorithms. Direction-of-arrival estimation. MIMO architecture: basic principles; capacity issues; BLAST algorithm. Space-time coding. Alamouti scheme. Spatio-temporal radio channels. Impact of correlation.

- **Weekly schedule (approx.):**
- **Week 1:** Introduction to wireless communications: generic system architecture and its main limitations. Propagation channel and interference effects. Motivation for using smart antennas.
- **Week 2-3:** Propagation channel: basic radio wave propagation mechanisms and its system-level effects. Traditional (“scalar”) propagation channel characterization. Spatio-temporal (“vector”) channel characterization.

- **Week 4:** Introduction to antenna arrays and smart antennas. Interference cancellation. Types of smart antennas: switched-beam, adaptive, diversity combining and multiple-input multiple output (MIMO). Range and capacity improvement. Space-division multiple access (SDMA).
- **Week 5-6:** Beamforming algorithms (MVDR, MMSE, max. SNR, eigenvector, etc.). Optimal spatial filtering. Direction-of-arrival estimation (Capon, MUSIC). Adaptive least squares.
- **Week 7-10:** Introduction to the MIMO architecture: high-level description & basic principles. MIMO channel capacity. Matrix channel modeling and impact of correlation.
- **Week 11-12:** Receiver algorithms: ZF and MMSE V-BLAST, ML. Space-time coding: basic principles, Alamouti scheme, diversity and coding gains. Performance analysis. Topics of current research interest (multi-user systems/networks & interference, security, cognitive radio, massive antennas/MIMO).
- Note: no electromagnetics in this course!

References: Books

1. H.L. Van Trees, Optimum Array Processing, Wiley, New York, 2002.
2. R.A. Monzingo, R.L. Haupt, T.W. Miller, Introduction to Adaptive Arrays (2nd Ed.), Scitech Publuishing, 2011. (1st Ed. -1980).

3. J.C. Liberti, Jr., T.S. Rappaport, Smart Antennas for Wireless Communications, Prentice Hall, Upper Saddle River, 1999.
4. D.H. Johnson, D.E. Dudgeon, Array Signal Processing, Prentice Hall, Upper Saddle River, 1993.
5. J.E. Hudson, Adaptive Array Principles, Peter Peregrinus, London, 1981.

6. E. Dahlman, S. Parkvall, J. Skold 5G NR: The Next Generation Wireless Access Technology, Academic Press, 2020.

7. T.K. Moon, W.C. Stirling, Mathematical Methods and Algorithms for Signal Processing, Prentice Hall, 2000.

References: Books on MIMO

8. D. Tse, P. Viswanath, Fundamentals of Wireless Communications, Cambridge University Press, 2005.
9. J.R. Barry, E.A. Lee, D.G. Messerschmitt, Digital Coomunications (3rd Ed.), Kluwer, Boston, 2004. – see Chapters 10 and 11.
10. R.W. Heath, A. Lozano, Foundations of MIMO Communications, Cambridge University Press, 2019.
11. P.P. Vaidyanathan et al, Signal Processing and Optimization for Transceiver Systems, Cambridge University Press, 2010.
12. L. Marzetta et al, Fundamentals of Massive MIMO, Cambridge University Press, 2016.
13. D.W. Bliss, S. Govindasamy, Adaptive Wireless Communications: MIMO Channels and Netwroks, Cambridge, 2013.
14. E. Biglieri et al, MIMO Wireless Communications, Cambridge University Press, Cambridge, 2007.
15. H. Bolcskei et al (Eds.), Space-Time Wireless Systems: From Array Processing to MIMO Communications, Cambridge University Press, Cambridge, 2006.
16. A. Paulraj, R. Nabar, D. Gore, Introduction to Space-Time Wireless Communications, Cambridge University Press, 2003.
17. G. Larsson, P. Stoica, Space-Time Block Coding for Wireless Communications, Cambridge University Press, 2003.

Papers (selected only):

1. Special Issue on MIMO Systems, IEEE Transactions on Signal Processing, v. 50, N. 10, Oct. 2002.
2. Special Issue on MIMO Systems, IEEE Journal Selected Areas Comm, v. 21, N. 3 and 5, April and June 2003.
3. Special Issue on Space-Time Transmission, Reception, Coding and Signal Processing, IEEE Trans. Information Theory, v. 49, N. 10, Oct. 2003.
4. Special Issue on Gigabit Wireless, Proceedings of the IEEE, v. 92, N.2, Feb. 2004.
5. Special Issue on Large-Scale Multiple Antenna Wireless Systems, IEEE Journal on Selected Areas in Communications (JSAC), vol. 31, no. 2, Feb. 2013.
6. Special Issue on Massive MIMO, Journal of Communications and Networks (JCN), vol. 15, no. 4, Aug. 2013.
7. Special Issue on Signal Processing for Large-Scale MIMO, IEEE Journal of Selected Topics in Signal Processing (JSTSP), Vol. 8, No. 5, Oct. 2014.
8. E. G. Larsson et al, Massive MIMO for Next Generation Wireless Systems, IEEE Communications Magazine, vol. 52, no. 2, pp. 186-195, Feb. 2014.
9. Special Issue on Signal Processing for Millimeter Wave Wireless Communications, IEEE Journal of Selected Topics in Signal Processing, vol. 10, no. 3, pp. 433-435, April 2016.

Papers (selected only):

10. L. Lu et al, An Overview of Massive MIMO: Benefits and Challenges, IEEE JSTSP, Vol. 8, No. 5, Oct. 2014.
11. F. Rusek et al, Scaling up MIMO: Opportunities and Challenges with Very Large Arrays, IEEE Signal Processing Magazine, vol. 30, no. 1, pp. 40-46, Jan. 2013.
12. H. Q. Ngo, E. G. Larsson, T. L. Marzetta, Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems, IEEE Trans. Comm., vol. 61, no. 4, pp. 1436-1449, Apr. 2013.
13. T.L. Marzetta, Massive MIMO: An Introduction, Bell Labs Technical Journal, v. 20, 2015.
14. R. W. Heath et al, An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems, *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 436-453, April 2016.

Useful Journals

- IEEE Transactions on Wireless Communications
- IEEE Transactions on Communications
- IEEE Transactions on Signal Processing
- IEEE Transactions on Antennas and Propagation
- IEEE Transactions on Information Theory
- IEEE Journal on Selected Areas in Communications (JSAC)
- IEEE Journal of Selected Topics in Signal Processing (JSTSP)
- IEEE Transactions on Vehicular Technology
- IEEE Signal Processing Magazine

How to Study: Learning Efficiency Pyramid

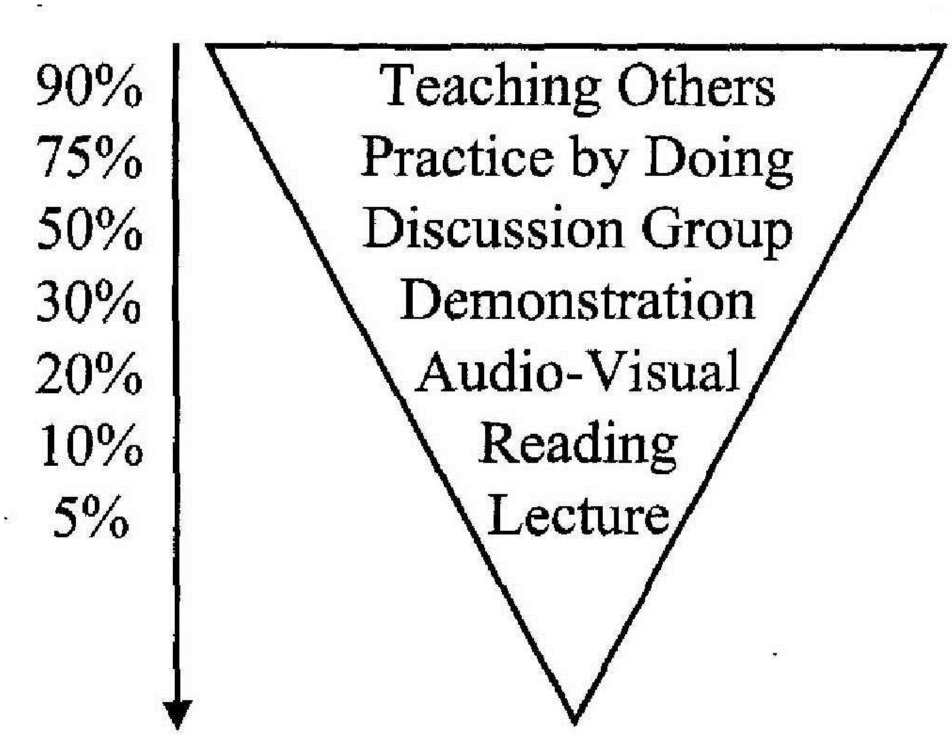


Figure 1. The Learning Pyramid, adapted from David Sousa, *How the Brain Learns*, Reston, VA, The National Association of Secondary School Principals, 1995, ISBN 0-88210-301-6.

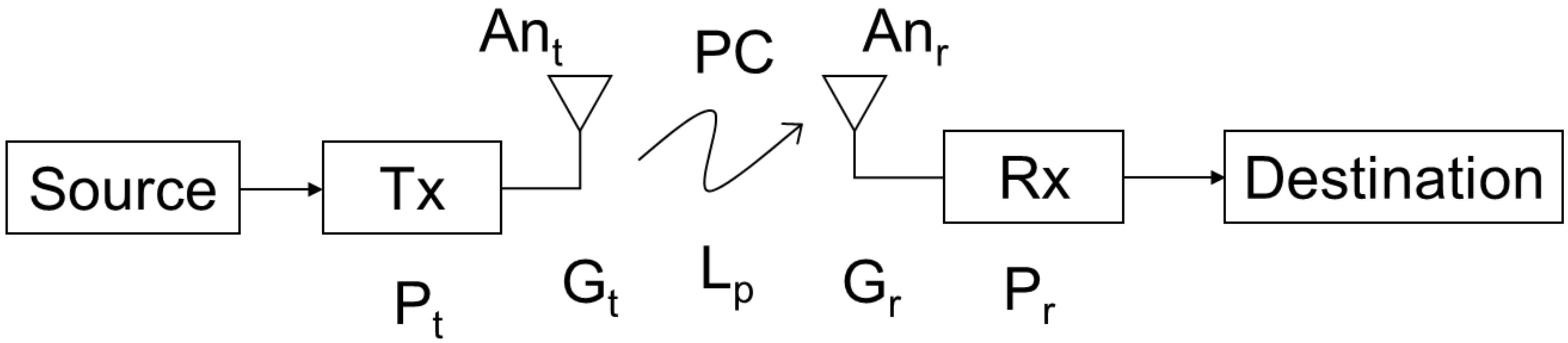
"Tell me and I'll forget; show me and I may remember; involve me and I'll understand." – old Chinese proverb.

"No pain, no gain" – common wisdom.

How to Study

- Learning efficiency pyramid is a good guideline
- Reading is necessary, but taken alone is not efficient
- Solving problems ("practice by doing")
  - is much more efficient
  - examples, assignments, end-of-chapter problems
- Group discussions
  - help provided you contribute something
- Systematic study during the semester
  - is a key to a success.
  - do not leave everything to the last day/night before exams!
- Lectures
  - should be supplemented by the items above

Basic Wireless System Architecture and Its Main Limitations



Source -> source of information to be transmitted

Destination -> destination of transmitted information

Tx and Rx -> transmitter and receiver

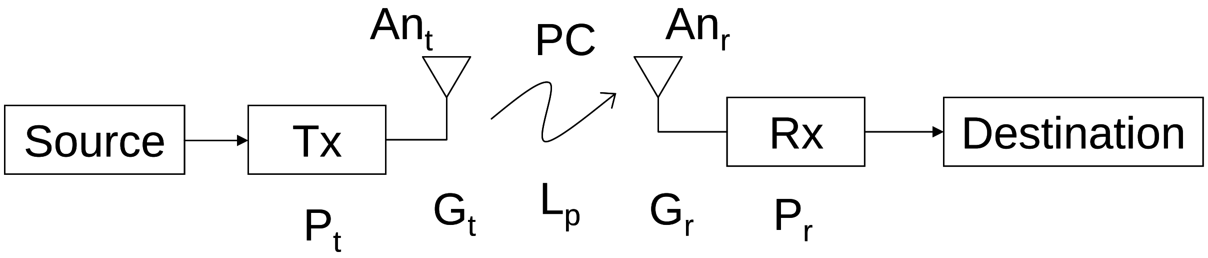
An_t & An_r -> Tx and Rx antennas

PC – propagation channel

- Tx includes coding/modulation circuitry(or DSP), power amplifiers, frequency synthesizers etc.
- Rx includes LNA, down conversion, demodulation, decoding etc.

- Examples: WiFi, cellular phones, radio and TV broadcasting, GPS, cordless phones, radar, etc.
- Main advantages: flexible (service almost everywhere), low deployment cost (compare with cable systems).
- Main disadvantages: PC is very bad, limits performance significantly, almost all development in wireless com. during last 50 years were directed to combat PC.

Simplified Link Budget Analysis



An_t PC An_r

Source → Tx → Rx → Destination

P_t G_t L_p G_r P_r

$$\boxed{P_r = \frac{G_r G_t P_t}{L_p}}$$

P_t – Tx power, P_r – received power, L_p – propagation loss, G_t and G_r – Tx and Rx antenna gains

In practice , some other factors are added (including safety margins),

Practical limits for G_r and G_t: $G_r, G_t \le (40 \sim 60)dB$

Fixed microwave systems: up to 40dB

Mobile systems: 2~3 dB (no smart antennas)

- P_r is limited from below (i.e, noise etc.)

$$P_r \geq P_{\min}$$

- to provide satisfactory performance. $P_{\min}$ – Rx sensitivity
- For given $P_{\min}$ and L_p (depends on geometry, propagation scenario), can find G_r, G_t, P_t (design trade-off)
- <u>Example</u>:

$$P_{\min} = 10^{-12}\,\mathrm{W}(-90\ \mathrm{dBm}); \quad L_p = 150\ \mathrm{dB}\ (10^{15});$$

$$G_r = 10\ \mathrm{dB}; \qquad G_t = 10\ \mathrm{dB};$$

$$P_t = \frac{P_{\min} L_p}{G_t G_r} = \left(P_{\min} + L_p - G_t - G_r\right)[dB] = 40 dBm = 10W;$$

Effect of Interference

- No interference -> SNR $\boxed{SNR = \gamma = \frac{P_{sig}}{P_{noise}}}$
- Interference -> SNIR $\boxed{SNIR = \gamma = \frac{P_{sig}}{P_{noise} + P_{\text{int}}}}$
- Satisfactory performance requires $\gamma = (10...30)dB$
- Minimum received power (no interf.): $\boxed{P_r \geq \gamma \cdot P_{noise}}$
- Minimum received power (interf.): $\boxed{P_r \geq \gamma\left(P_{noise} + P_{\text{int}}\right) > \gamma P_{noise}}$
- The effect of interference is to boost the required Rx power.

Free Space Propagation Loss

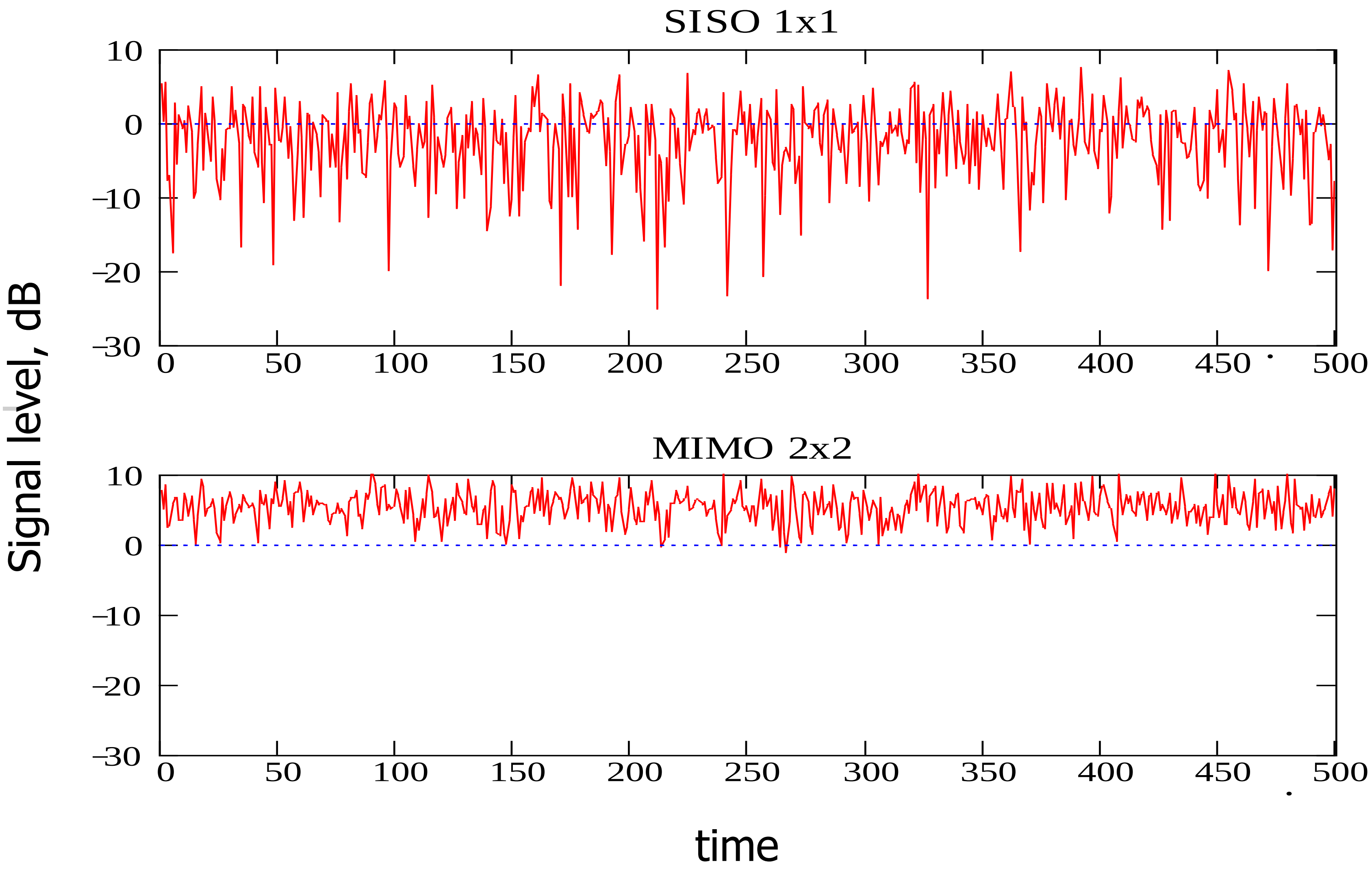
- LOS is not obstructed, no multipath etc.

$$\boxed{L_p = \left(\frac{4\pi R}{\lambda} \right)^2}$$

- Example: $f_0 = 10GHz(\lambda_0 = 3cm); R = 100km; L_p \approx 10^{15} = 150dB$
- Multipath propagation, obstruction of LOS etc. can significantly increase Lp.
- Its value is very large and must be compensated by other system components
- This is not the only problem with PC, multipath results in fading, which results in Lp variations (in time and space) up to 30~40 dB or more down (sometimes even more!), this must be compensated for as well.

- However , while all the other system components (i.e., Tx, Rx, Ant, Anr) are well under control, PC is out of our control, Then there is nothing we can do about it (with small exceptions).
- Hence, all the system design is directed to compensate the effect of PC.
- Smart antennas can be effective tool in compensating for PC effects; much more efficient than other system components.

Fading Channel Example



BER of AWGN and Fading Channels

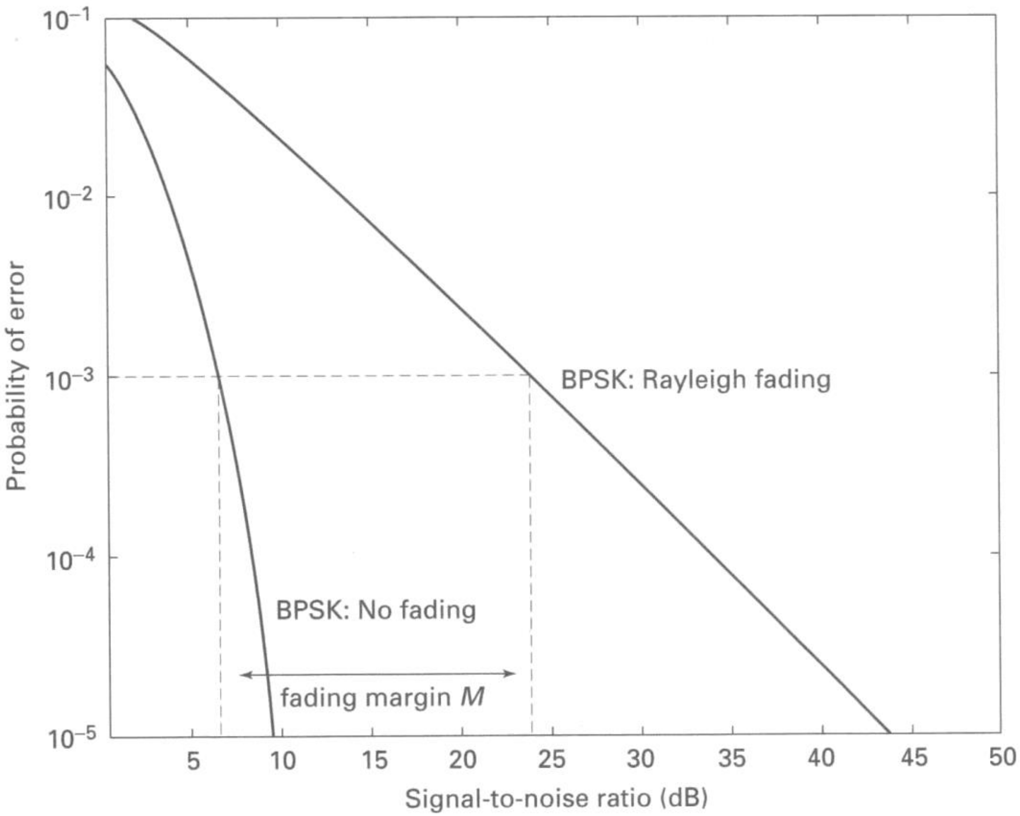


FIGURE 5.1 Probability of error for coherent BPSK in the presence of Rayleigh fading and in the absence of fading.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

BER of Fading Channels with CCI

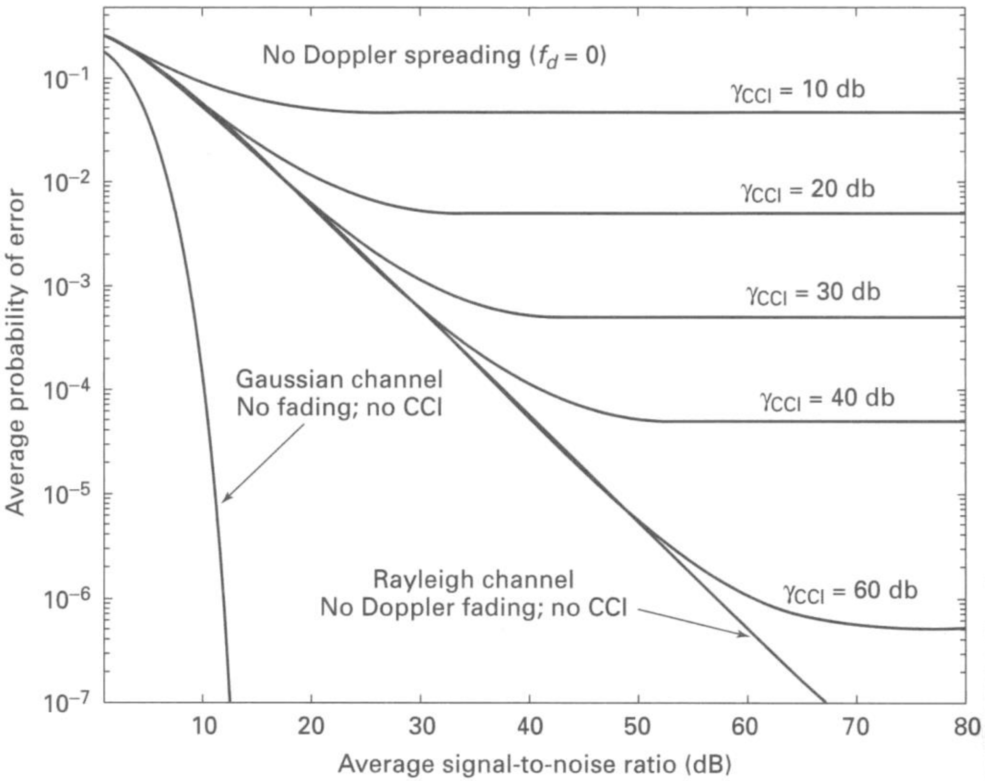


FIGURE 5.5 Error floor behavior in the presence of CCI fading for the case of MSK with a differential detector.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

BER of Fading Channels with Diversity

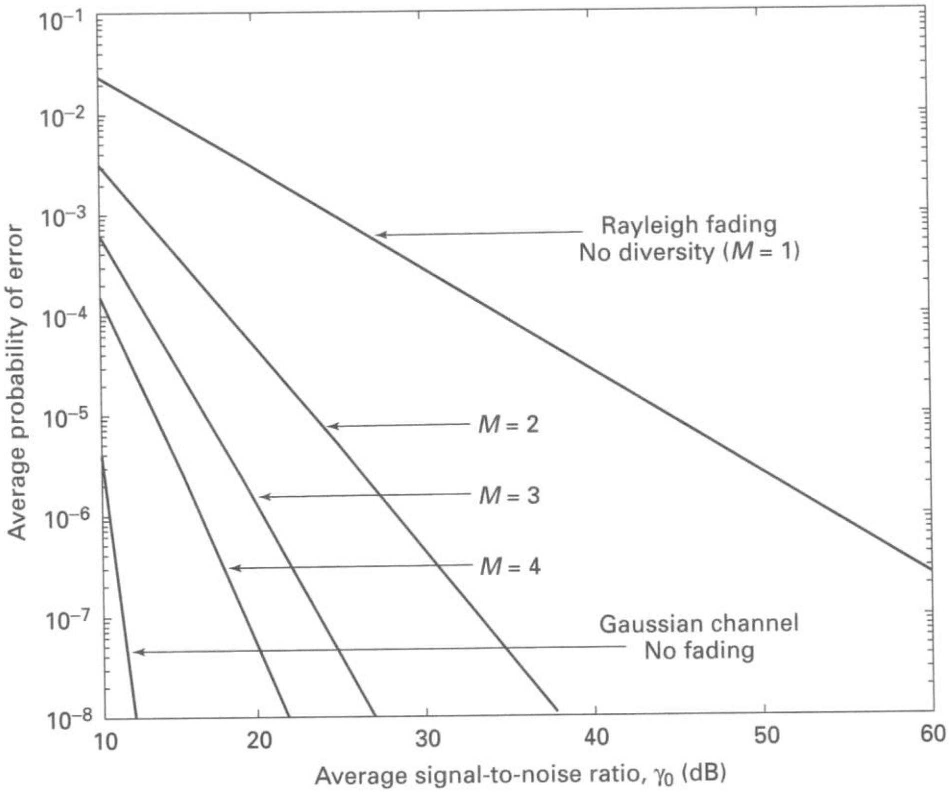


FIGURE 5.18 The average probability of error for the selection combiner for the case of coherent BPSK.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

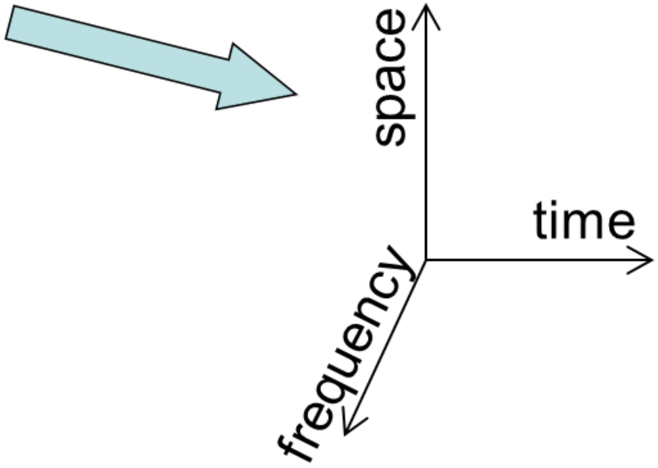
Motivation for Using Smart Antennas

- System performance is limited by PC and external interference (i.e., other users etc.). Need some tools to improve it
- Time-domain and frequency domain techniques (coding, modulation, filtering, etc.) have been extensively studied in past 50 years.
- These techniques are at their limits, improvement is very small (fraction of a dB).
- What is a smart antenna: multiple antenna elements (antenna array) + appropriate signal processing
- Spatial processing, implemented in the form of a smart antenna, is not much used (and not understood so well). Hence, the potential of this field is tremendous -> it is “the last frontier”.

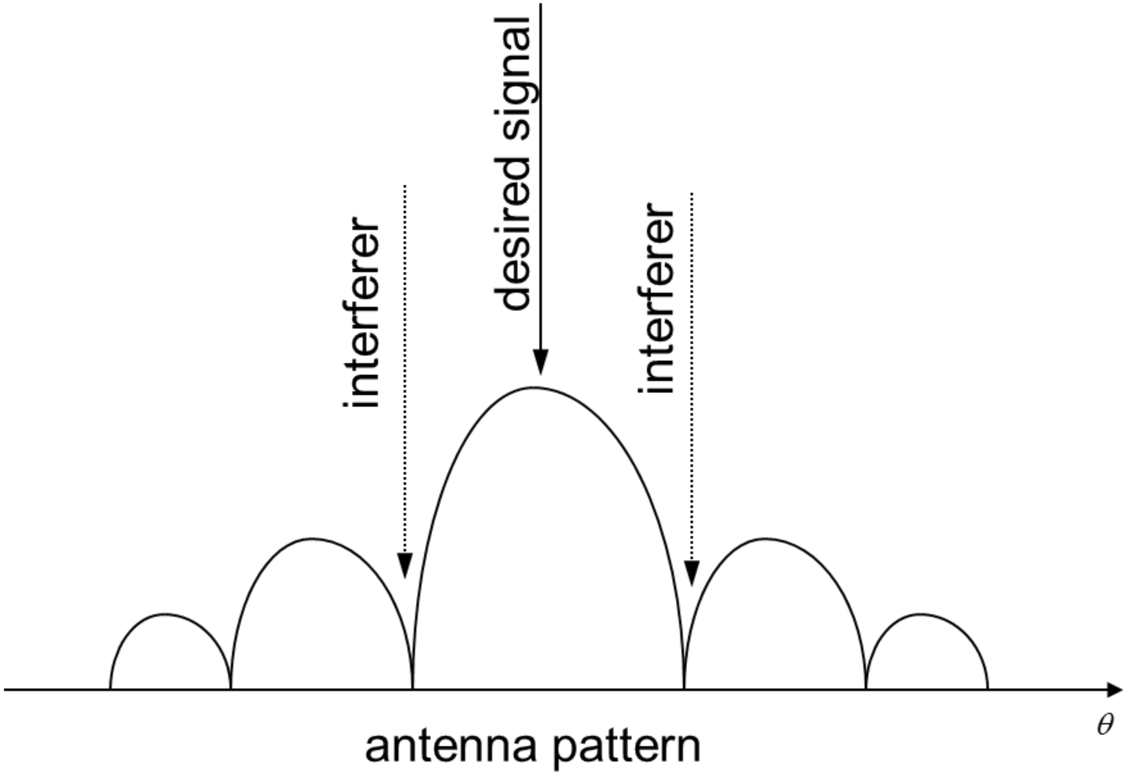
What can be done using smart (adaptive, intelligent) antennas:

- Increase in range (coverage), can be traded-off for battery life, decreased Tx power or Rx sensitivity (noise floor).
- Increase in capacity (both bit/s/Hz (spectrum efficiency) and users/sector).
- Increase in quality of service and to provide new services (position location).
- Smart antennas can also be used to reduce delay spread and to slow down channel variations.
- All this is accomplished by spatial signal processing—may be thought of as a spatial filtering.
- Spectrum efficiency can be trade-off for increased data rate.
- Capacity increase – SDMA (similar to FDMA and TDMA)
- Many users in the same bandwidth

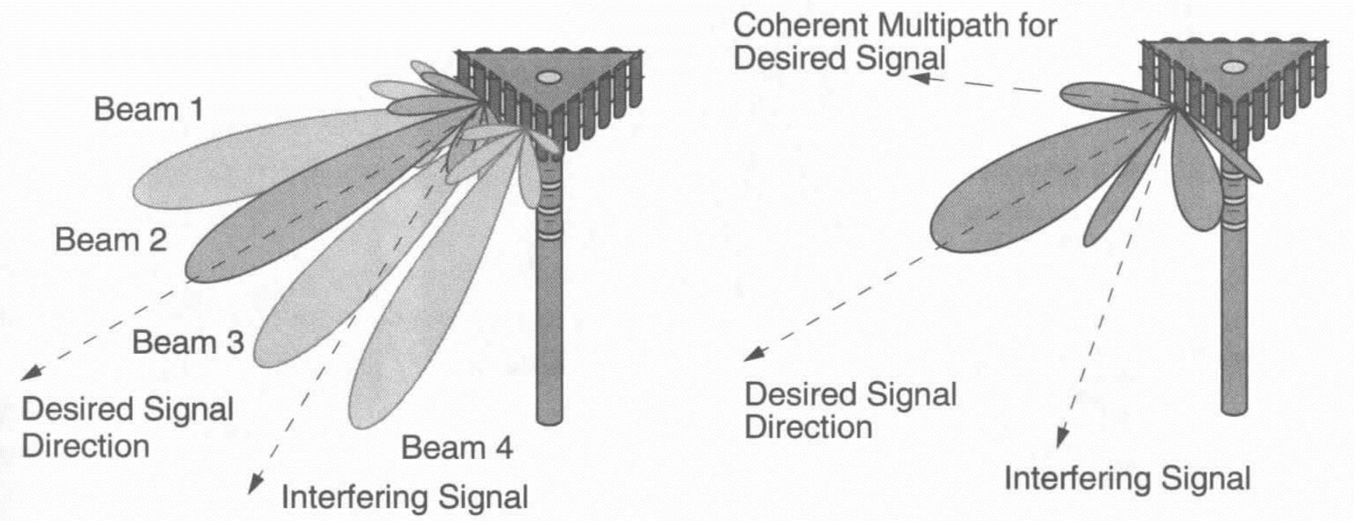
- Fundamentally, a new dimension is added to signal processing: 2-D -> 3-D !



objective:



Smart Antennas: Why?



(a) Switched Beam Systems can select one of several beams to enhance receive signals. Beam 2 is selected here for the desired signal.

(b) An adaptive antenna can adjust its antenna pattern to enhance the desired signal, null or reduce interference, and collect correlated multipath power.

J.C. Liberti, Jr., T.S. Rappaport, Smart Antennas for Wireless Communications, Prentice Hall, 1999.

WiFi MIMO (multi-antenna)

- “MU-MIMO – the latest innovation in WiFi”
- Commercially-available WiFi MIMO routers
  - Linksys, Belkin, Motorolla etc.

Cellular MIMO

- "The last frontier"
- Commercially-available systems (LTE)
  - Ericsson, Motorolla, etc.
- "Ericsson 5G delivers 5 Gbps speeds" (07.2014)

Massive MIMO for 5G*

- 5G: the latest wireless system standard (cellular), still under development
- Significant improvement over 4G (current)
- Several key new technologies:
  - Millimeter waves
  - Hybrid networks, small cells, aggressive frequency re-use
  - **Massive MIMO (multi-antenna)****

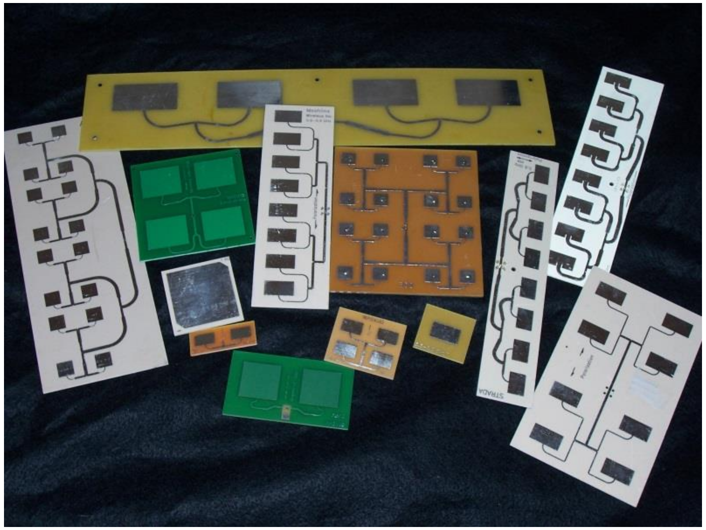
* J. G. Andrews et al, What Will 5G Be?, IEEE JSAC, vol. 32, no. 6, pp. 1065-1072, Jun. 2014.

* M. Shafi et al, 5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice, IEEE JSAC, Part I & II, v. 35, N.6 & 7, Jun. & Aug. 2017.

** Special Issue on Large-Scale Multiple Antenna Wireless Systems, IEEE JSAC, vol. 31, no. 2, Feb. 2013.

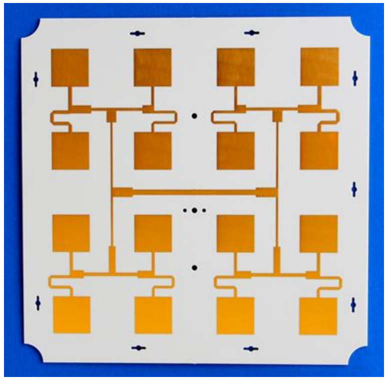
** E. G. Larsson et al, Massive MIMO for Next Generation Wireless Systems, IEEE Communications Magazine, vol. 52, no. 2, pp. 186-195, Feb. 2014.

Implementation of Antenna Arrays



http://www.wa5vjb.com/

http://www.mifi-hotspots.com



www.cst.com

5G Implementation

64-element array at 28 GHz

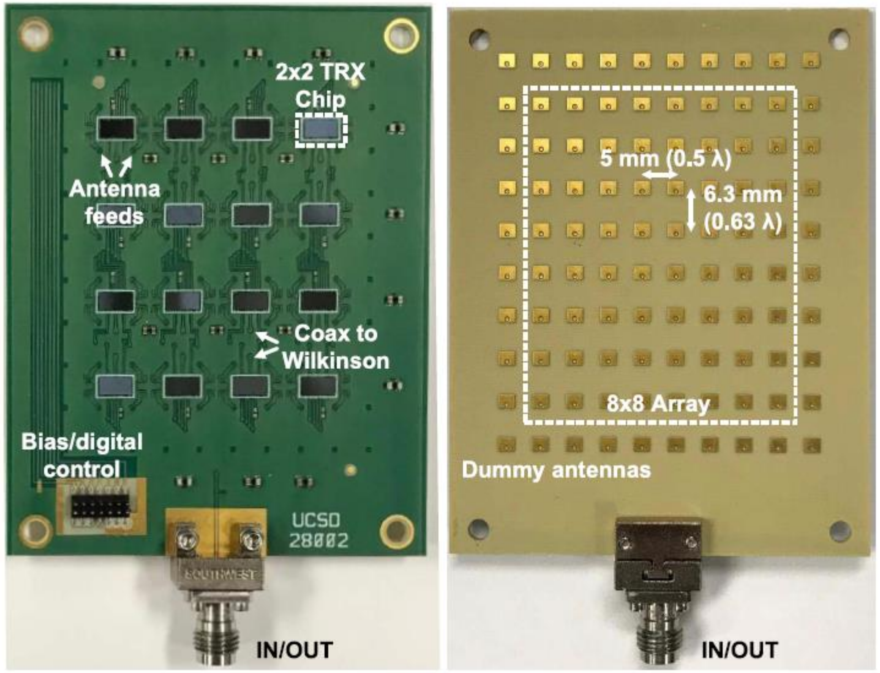
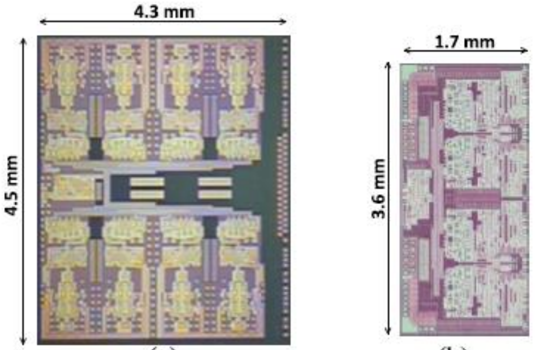


Fig. 9. Top and bottom views of the 64-element array PCB with flip-chip beamformer ICs and PCB integrated stacked-patch antennas.

K. Kibaroglu et al, A 64-Element 28-GHz Phased-Array Transceiver with 52-dBm EIRP and 8–12-Gb/s 5G Link at 300 Meters Without Any Calibration, IEEE Trans. Microwave Theory Tech., vol. 66, no. 12, Dec. 2018.

5G Implementation

32-element array at 38 GHz



(a) (b)

Fig. 6. Chip photographs of (a) eight-channel Tx and (b) four-channel Rx phased array beamformers [23].

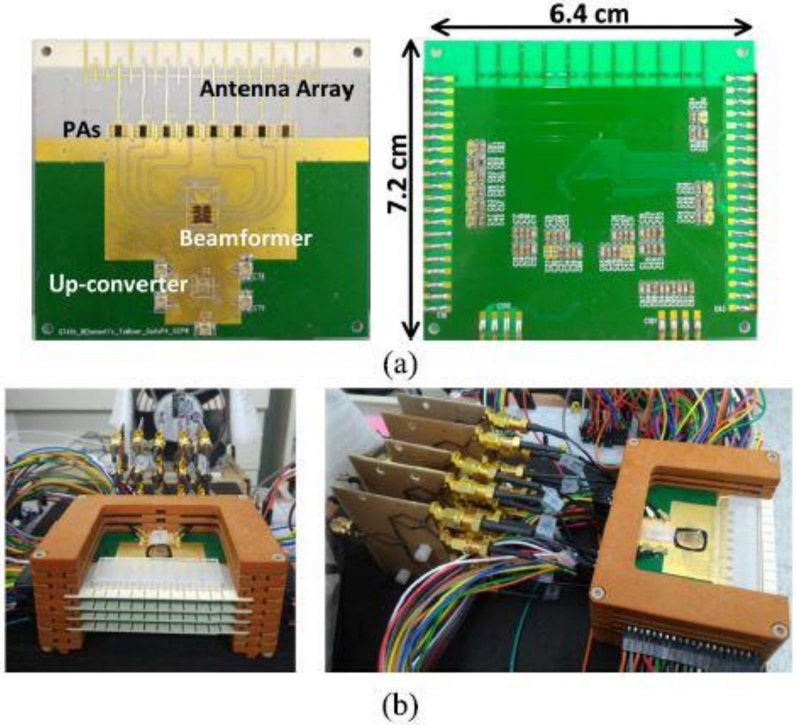


Fig. 25. Photographs of (a) proposed eight-element phased array Tx PCB module and (b) implemented 32-element phased array Tx.

C.N. Chen et al, 38-GHz Phased Array Transmitter and Receiver Based on Scalable Phased Array Modules With Endfire Antenna Arrays for 5G MMW Data Links, IEEE Trans. Microwave Theory Tech., Nov. 2020.

How Large is a Feasible N?

- And N=1000?
  - J. Hoydis et al, “Massive MIMO in UL/DL cellular systems: How many antennas do we need,” IEEE JSAC, Feb. 2013
- Only academic? In practice?

ᗢ F-16/MIG-29/SU30 (~1000)

AN/APG-68(V)9 F-16 Multimode Fire Control Radar, adopted from Northrop Grumman

ᗢ Patriot (~5000)

MIM-104 Patriot Radar, adopted from Wikipedia

How Large is a Feasible N?

- Maybe N=10000?

- S300 (10000)

D.K Barton, Design of the S-300P and S-300V Surface-to-Air Missile Systems, 2009.

How Large is a Feasible N?

- Can it be N > 10,000?

  - Cobra Dane (34,000)

COBRA DANE, an intelligence-gathering phased array radar, Shemya Air Force Base, Alaska, adopted from Wikipedia

How Large is a Feasible N?

- What about N > 100,000?

- Don 2 radar (250,0000), 4 x 30m x 130m

Don-2 missile defense radar, Moscow region, Russia, adopted from Wikipedia