Sharif University of Technology

Tehran, Iran

Principles of Phased Array Systems

A graduate course in Electronics

Tutorial I

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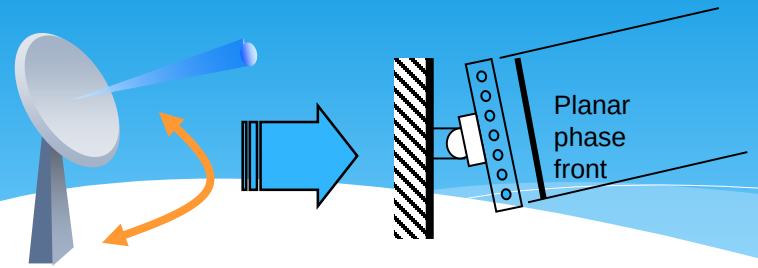
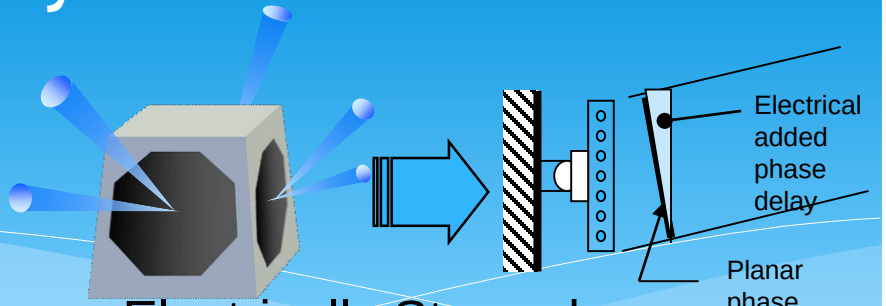
Room 511

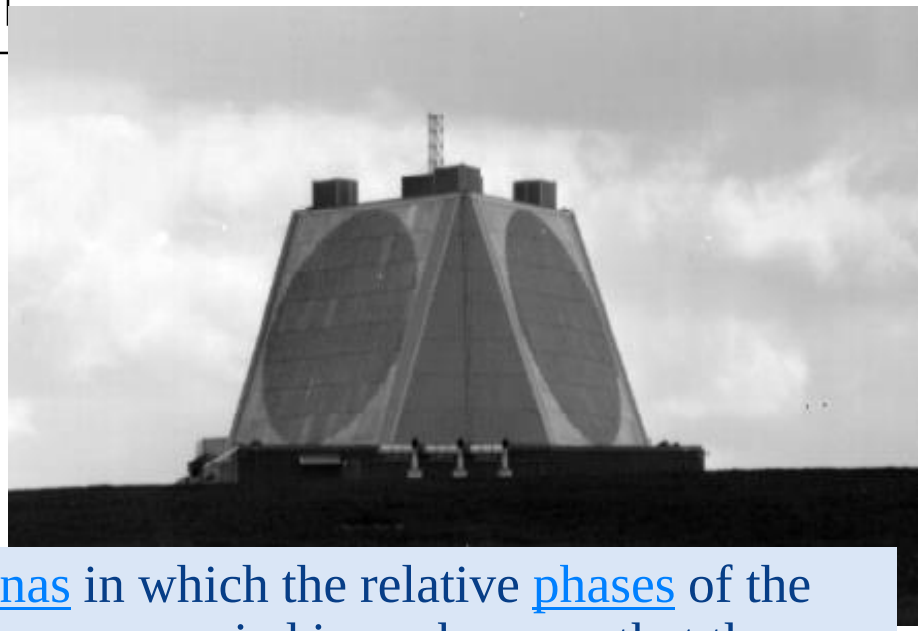
Phased Array Radar



Mechanically Steered,
Rotating Reflector Array



Electrically Steered,
Fixed Phased Array

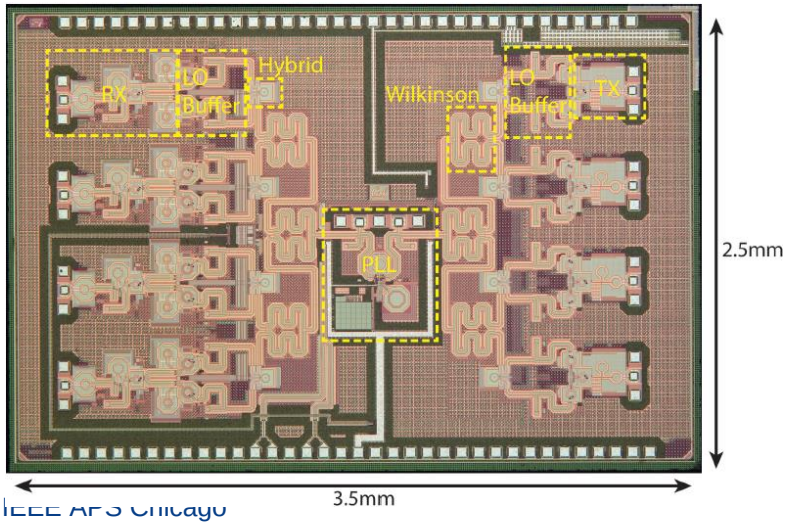


* "A phased array is a group of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions." *wikipedia*

اصول سیستمهای آرایه فازی

مباحث ویژه در الکترونیک

32 m



* سیستم های آرایه فازی یکی از پیشرفته ترین سیستمهای الکترونیکی و مخابراتی محسوب می شوند که هفتاد سال پیش برای کاربردهای نظامی (رادار) پدید آمدند.

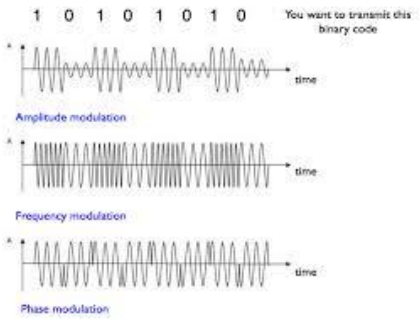
توانایی جابجایی پرتو آنتن بدون نیاز به چرخش مکانیکی سازه آنتن، امکان انجام چند عملیات مختلف با یک سیستم، یا انجام بسیار سریع یک عمل را فراهم می کند.

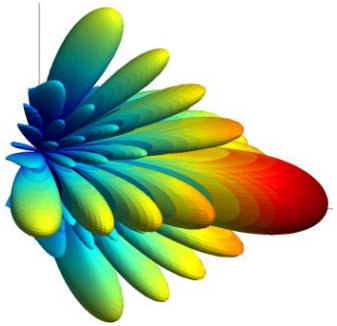
با پیشرفت تکنولوژی نیمه هادی سیستمهای آرایه فازی مجتمع در فرکانسهای موج میلی متری و تراهرتز طراحی و ساخته شده اند که کاربردهای جدیدی را در سالهای آینده عرضه خواهند کرد.

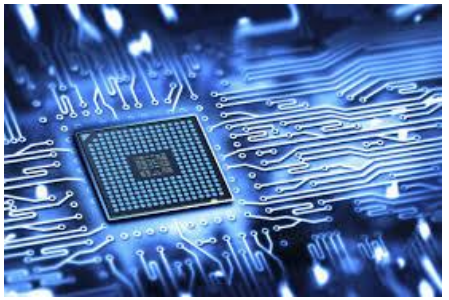
اصول سیستمهای آرایه فازی

مباحث ویژه در الکترونیک

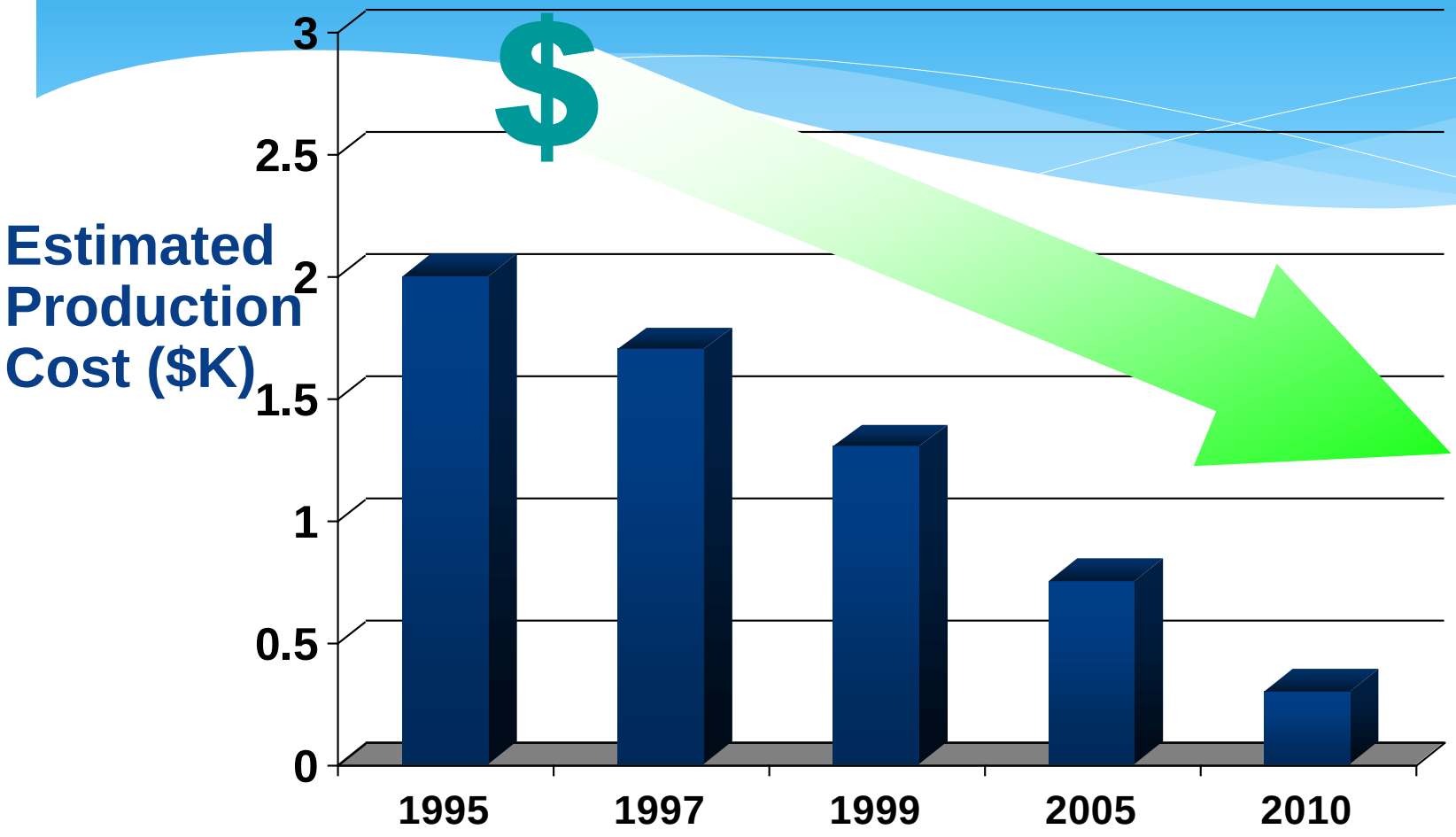
- درک نحوه عملکرد سیستم آرایه فازی نیازمند مجموعه ای از دانشهای گوناگون است، از الکترونیک گرفته تا مخابرات سیستم.
- **هدف از این درس آشنایی با اصول، اجزا، مدارات و تکنولوژی ساخت سیستم آرایه فازی است.**
- **ارزشیابی**: میان ترم، پایان ترم و تمرین و پروژه







Transmit/Receive (T/R) Module Cost Trends



Prices for Solid-State T/R Modules are Trending Downward

Instructor

Mohammad Fakharzadeh, PhD

Antenna & Packaging Manager, Peraso Technologies (2010-Present)

- Mm-wave Single antenna radio, Waveguide Modules
- 60 -70 GHz Phased array for portable electronics
- Low-cost packaging, Substrate, Ceramic, PCB and interposer Technologies

Post-doctoral fellow, ECE Department University of Waterloo (2009-2010)

- Leader of millimeter-wave wireless group
- Developing 60 GHz phased array receiver and transmitter for multi Gb/s data rates
- Designing high efficiency small on-chip/off-chip antennas

Antenna and Signal Processing Engineer, Intelwaves Technologies, Waterloo, Canada (2005-200 8)

- Mobile satellite communication systems
- Beamforming algorithms for phased array antenna.
- Array Antenna Simulation.
- Spectrum Analysis of Satellite Signals.

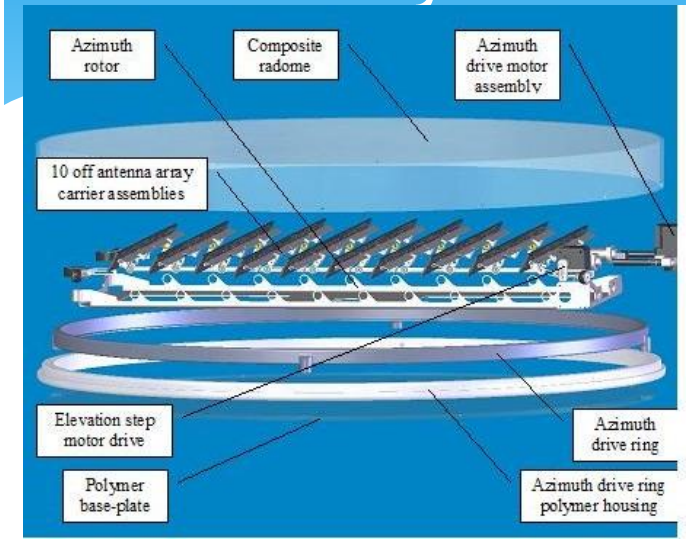
Research/Teaching Assistant, ECE Department University of Waterloo (Sept. 04- Nov 08)

- Development of fast and efficient beamforming and tracking algorithms
- Mobile wireless communication
- Array Antenna design
- Optical delay lines

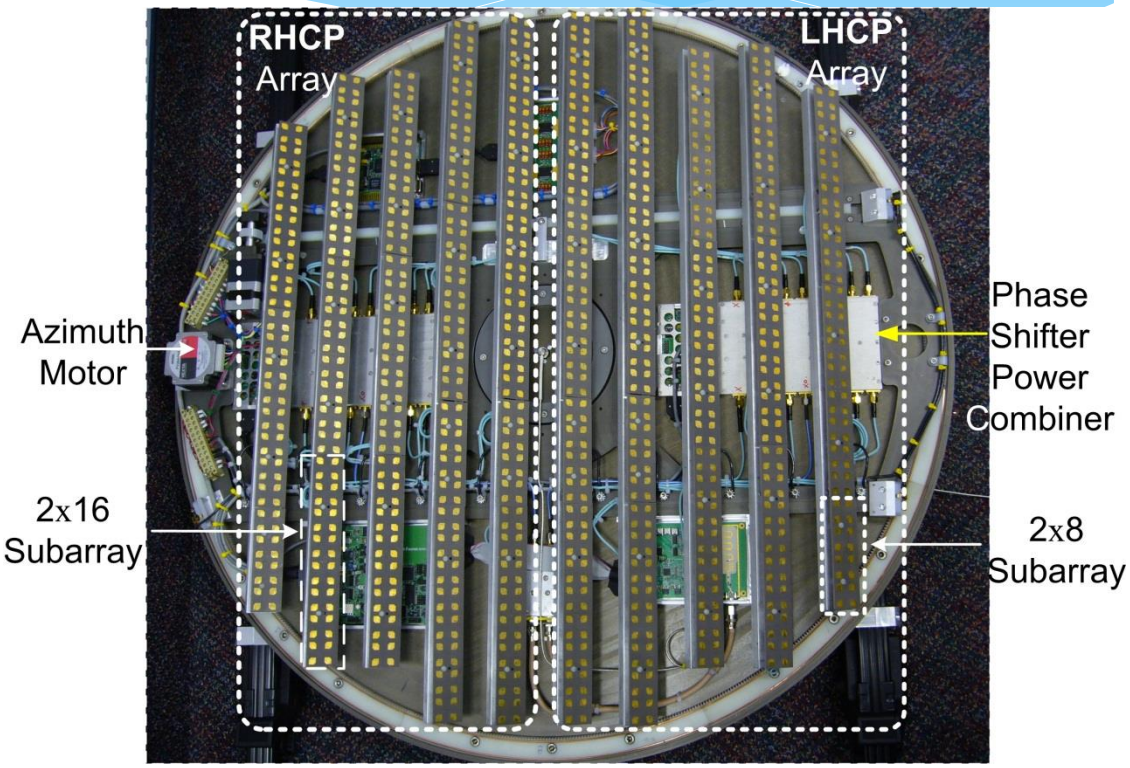
Research Assistant , Electrical Eng., Sharif University of Technology (2000-2002)

- System design of Phased Array Radar

Ku-band 1000 Element Mobile Phased Array for Satellite communication



Parameters	Value
Frequency	12.2-12.7 GHz
Polarization	Dual Circular
Gain	31.5 dB (per polarization)
Axial ratio	<1.8 dB
Tracking speed (Azimuth)	60°/sec
Spatial coverage	0°-360° Azimuth 20°-70° Elevation
System height	6 cm
System diameter	86 cm
System weight	12 Kg



References

[1] RC Hansen, Phased array antennas, 2009, 2nd Ed, Academic press.

[2] R. J. Mailloux, Phased array antenna handbook, 2nd Ed. Artech House, 2005.

[3] M. Fakharzadeh, Optical and Microwave Beamforming for Phased Array Systems, PhD thesis, University of Waterloo, Nov 2008.

[4] A. Hajimiri, et al., Integrated phased array systems in silicon, Proceedings of the IEEE, vol. 93, no. 9, pp. 16371655, 2005.

[5] Alberto Valdes-Garcia, et al., A fully integrated 16-element phased-array, transmitter in SiGe BiCMOS for 60-GHz communications, IEEE J Solid-State Circuits, vol. 45, no. 12, pp. 2757, 2773, 2010.

[6] M. Fakharzadeh, et al., CMOS Phased Array Transceiver Technology for 60 GHz Wireless Applications, IEEE Trans. Antennas and Propagation, vol. 58, no. 4, pp. 1093-1104, 2010.

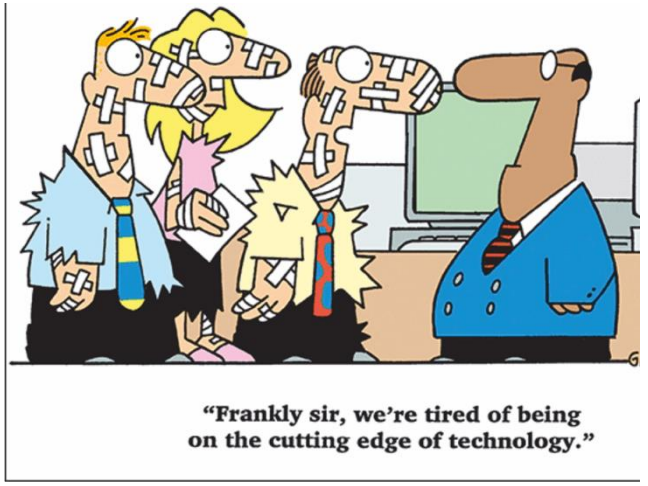
[7] Gabriel M. Rebeiz, et al. "RF MEMS phase shifters: design and applications." Microwave Magazine, IEEE 3.2 (2002): 72-81.

[8]- Eli Brookner, Practical Phased Array Antenna Systems, Artech House, 1991.

[9] …

Practice how to do research

* Know your tools
  * Research/documentation tools
* Work hard
* Stay at the cutting edge
* Read latest as well as classic papers
* Experiment or at least simulation



Research Tool

LaTeX

* High typeset quality
* Easy to include math formulas
* Source file format is not bounded to a particular OS or platform
* Latex implementations exists for all platforms: Linux, Windows,
* Latex is free
* All reports must be written with Latex
* Any Word document →

Neat Formula

```
\oint_{x=0}^{x=x_0}\int_{0}^{y_0}\sum_{i=1}^{n}\left [ \frac{\frac{\partial^2
}{\partial x^2}x^n\sqrt[n]{y}}{y_nx_n} \right ]
```

gif | Latin Modern | (10pt) Normal | 110 | Transparent | Inline | Compressed

$$\oint_{x=0}^{x=x_0}\int_{0}^{y_0}\sum_{i=1}^{n}\left[\frac{\frac{\partial^2}{\partial x^2}x^n\sqrt[n]{y}}{y_nx_n}\right]$$

Research Tools

zotero

* A free, easy-to-use tool to help you **collect, organize, cite, and share** your research sources.
* Notable features include web browser integration, online syncing, generation of in-text citations, footnotes and bibliographies, as well as integration with the word processors
* It is produced by the Center for History and New Media of George Mason University (GMU).

سرفصل ها

- مقدمه
- تاریخچه و کاربرد سیستمهای آرایه فازی
- سیستمهای آرایه فازی موج میلی متری
- تئوری آنتن آرایه فازی
- طراحی سیستمی آنتن آرایه فازی معماری سیستمهای آرایه فازی
- مدارات تغییر دهنده فاز

* سیستمهای آرایه فازی مجتمع
* کالیبراسیون و عیب یابی سیستمهای آرایه فازی الگوریتم های پرتوسازی
* پکجینگ تراشه و آنتن آرایه فازی
* آینده سیستمهای آرایه فازی و جمع بندی درس

Phased Array History

2012 IEEE APS Chicago

The Development of Phased-Array Radar Technology

Alan J. Fenn, Donald H. Temme, William P. Delaney, and William E. Courtney

Lincoln Laboratory has been involved in the development of phased-array radar technology since the late 1950s. Radar research activities have included

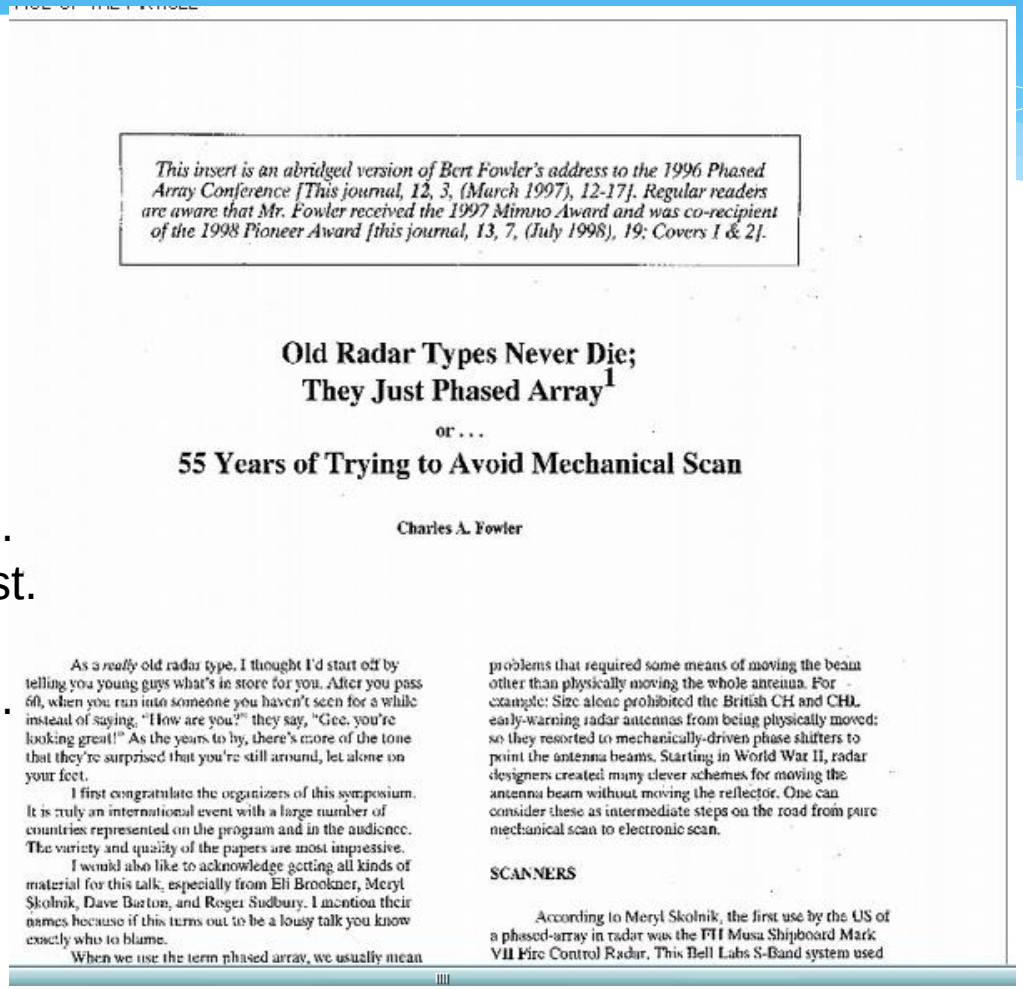
Old History

• The Army's "bed spring" array, which first bounced radar signals off the moon in the mid-1940s, is an example of an early array radar.

• During World War II, Nobel Laureate Luis Alvarez used phased array transmission in a rapidly-steerable radar system for " ground-controlled approach", a system to aid in the landing of airplanes in England.

•1950s could be characterized as "one thousand ways to steer a radar beam."

55 years History of Phased Array



This insert is an abridged version of Bert Fowler's address to the 1996 Phased Array Conference [This journal, 12, 3, (March 1997), 12-17]. Regular readers are aware that Mr. Fowler received the 1997 Mimno Award and was co-recipient of the 1998 Pioneer Award [this journal, 13, 7, (July 1998), 19; Covers 1 & 2].

Old Radar Types Never Die; They Just Phased Array[1]

or . . .

55 Years of Trying to Avoid Mechanical Scan

Charles A. Fowler

As a *really* old radar type, I thought I'd start off by telling you young guys what's in store for you. After you pass 60, when you run into someone you haven't seen for a while instead of saying, "How are you?" they say, "Gee, you're looking great!" As the years to by, there's more of the tone that they're surprised that you're still around, let alone on your feet.

I first congratulate the organizers of this symposium. It is truly an international event with a large number of countries represented on the program and in the audience. The variety and quality of the papers are most impressive.

I would also like to acknowledge getting all kinds of material for this talk, especially from Eli Brookner, Meryl Skolnik, Dave Barton, and Roger Sudbury. I mention their names because if this turns out to be a lousy talk you know exactly who to blame.

When we use the term phased array, we usually mean problems that required some means of moving the beam other than physically moving the whole antenna. For example: Size alone prohibited the British CH and CHL early-warning radar antennas from being physically moved; so they resorted to mechanically-driven phase shifters to point the antenna beams. Starting in World War II, radar designers created many clever schemes for moving the antenna beam without moving the reflector. One can consider these as intermediate steps on the road from pure mechanical scan to electronic scan.

SCANNERS

According to Meryl Skolnik, the first use by the US of a phased-array in radar was the FH Musa Shipboard Mark VII Fire Control Radar. This Bell Labs S-Band system used

Bert Fowler IEEE Aerosp. Electron. Syst. Mag. 13 (9), 1998, pp. 24A–24L

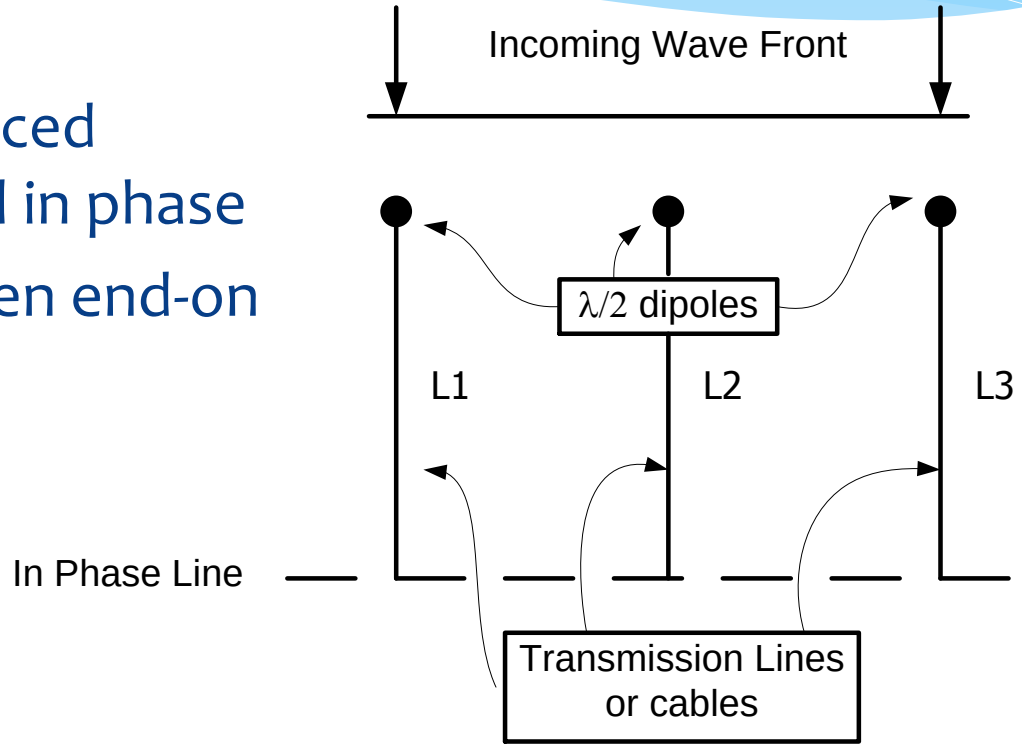
The dream of electronic beam movement was achievable, but it has taken a long time to achieve the dream, and it is not yet fully realized—we still need to reduce the cost of phased-array radars.

Phased Array Terminology

* Electronically Scanning Array Antenna (ESA)
* Smart Antenna
* Adaptive Array Antenna
* Beamforming Antenna
* Inertia-less Scanning Antenna

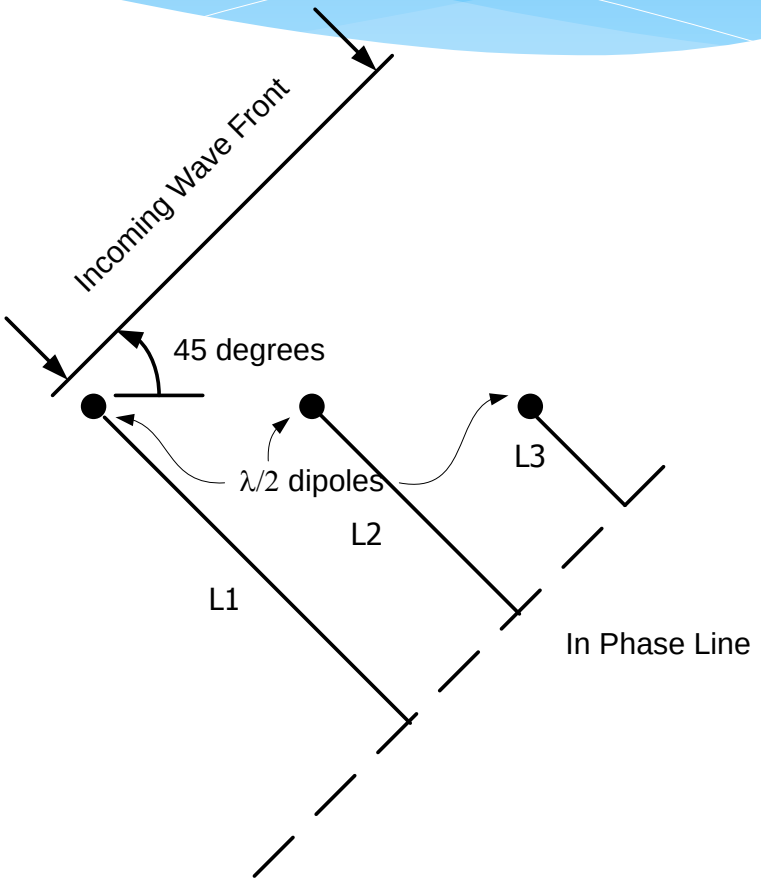
Design Example: 3 element array

* λ/2 dipoles
* If L1=L2=L3, induced voltages will add in phase
* Antennas are seen end-on



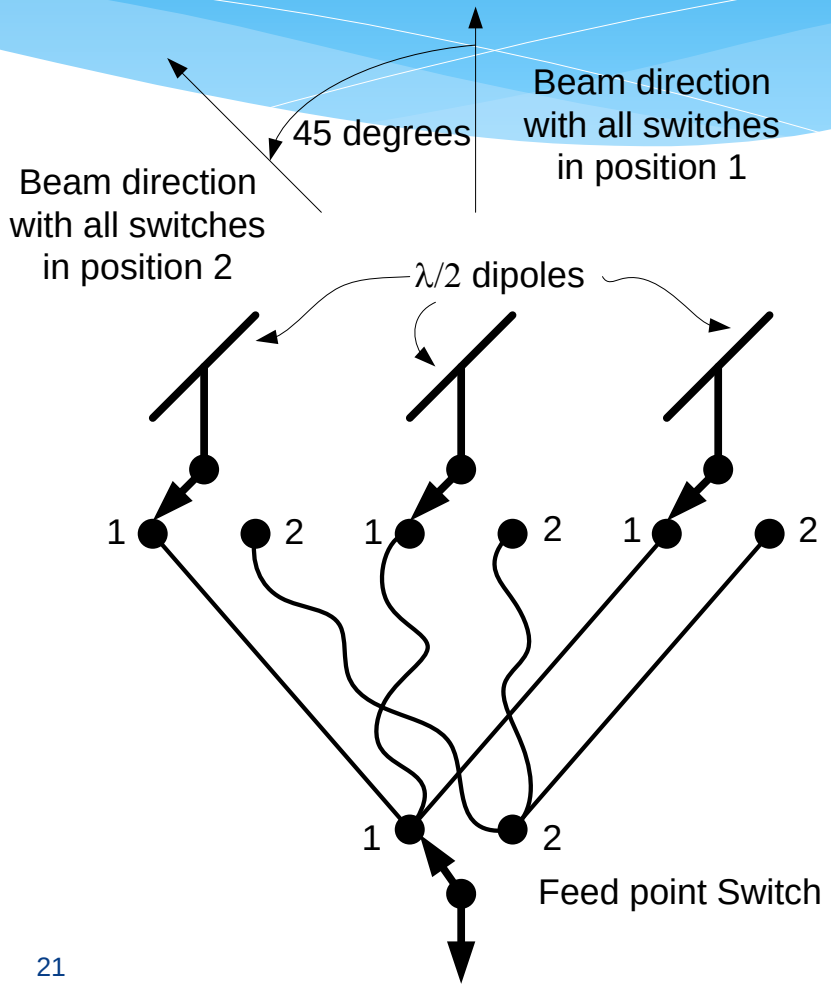
Design Example: 3 element array

* Consider a wave traveling at 45° from the broadside
* We want to have max sum
* The in-phase line is parallel to the wave front
* L1 ≠ L2 ≠ L3



Design Example: 3 element array

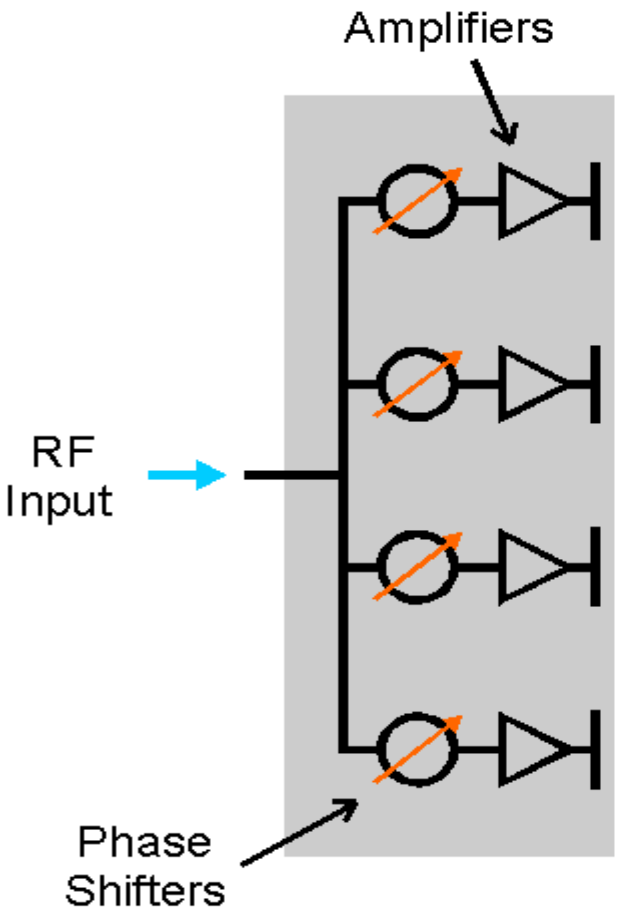
* By installing a switch at each antenna element and one at the common feed point and mechanically changing all switches together, the beam can be shifted from broadside to 45° by operating the switch



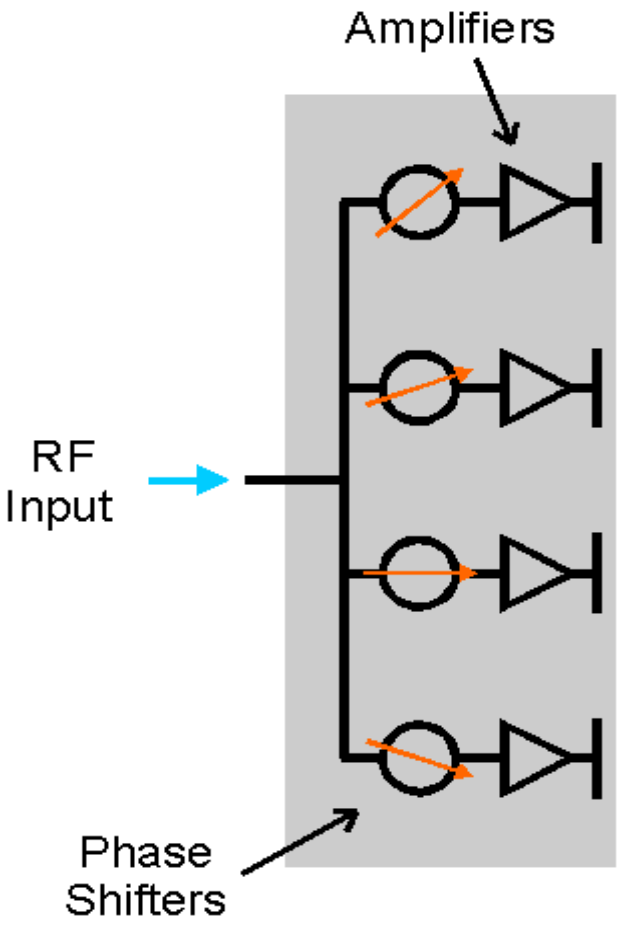
Design Example: 3 element array

* Instead of controlling the beam by switching cables, a phase shifter can be installed at each element
* The same effect can also be accomplished by inserting small sections of cable
* $\lambda/4$, $\lambda/2$, and $3\lambda/4$ will provide phase increments of 90°, but smaller increments can be used

Zero Phase Shift Animation



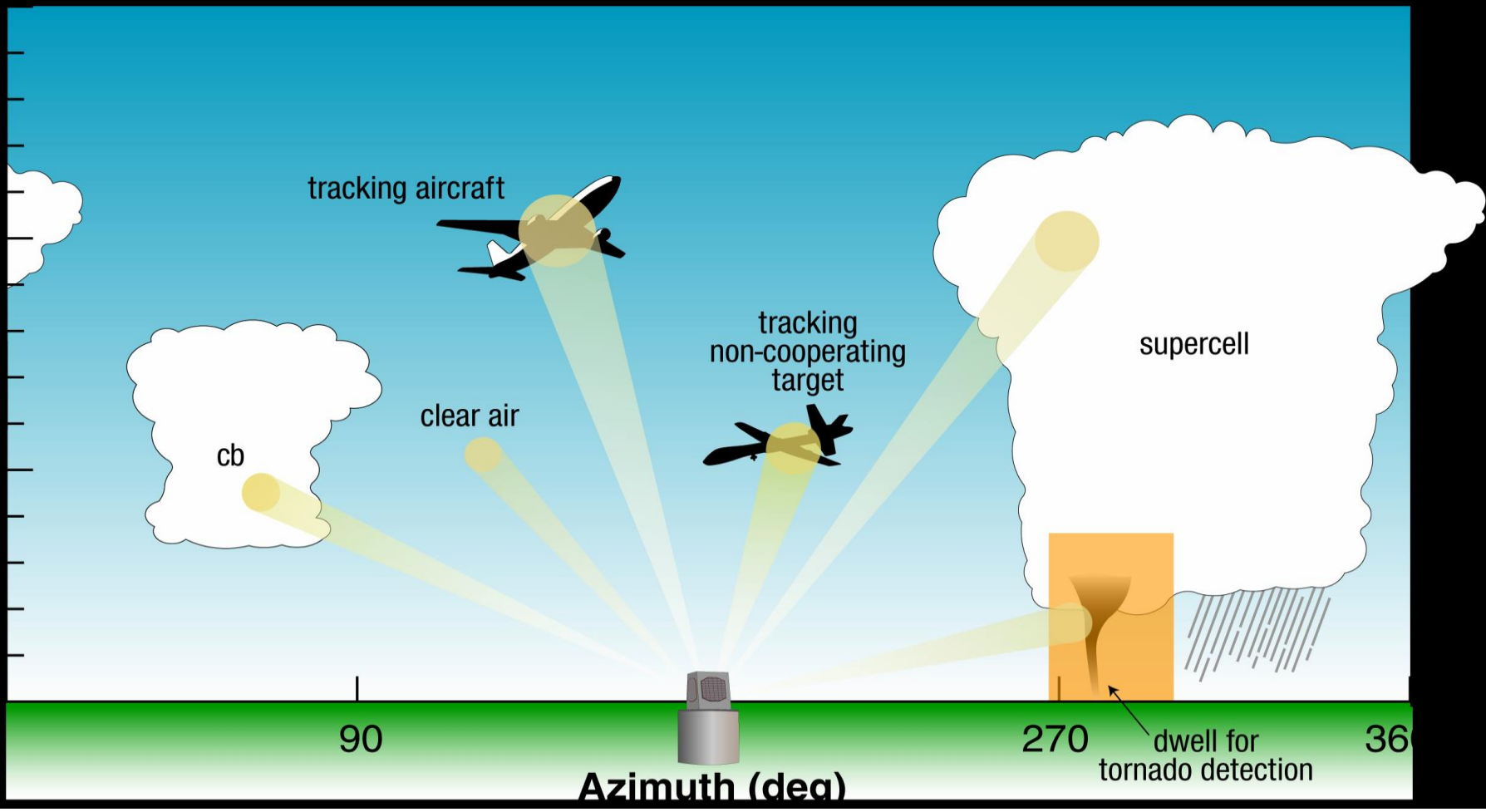
Constant Phase Shift Animation



Advantages- Electronic Scanning

* Accomplish beam steering electronically, without the mechanical and inertial problems of rotating an entire array
* Used where rapid target tracking is required
* Direction finding
* Communications applications where the radiation pattern must be adjusted to accommodate varying traffic conditions

Multi-functional Adaptive Scanning

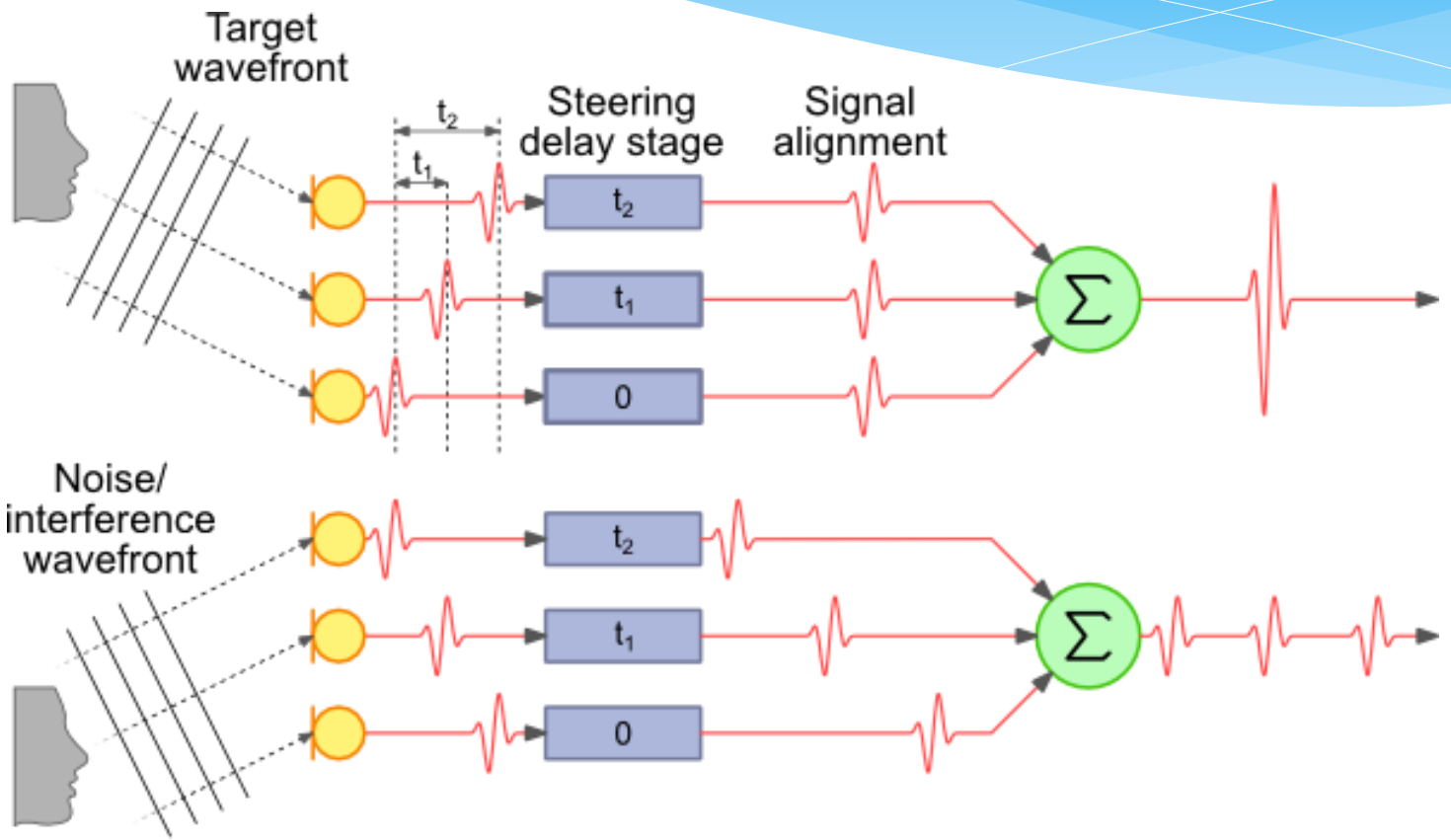


Advantages- Higher Signal Strength

* At high frequencies the output power of PA is limited (e.g. Psat<10 dBm in 65 nm CMOS at 60 GHz)
* Spatial power combination

Advantages- NLOS Transmission

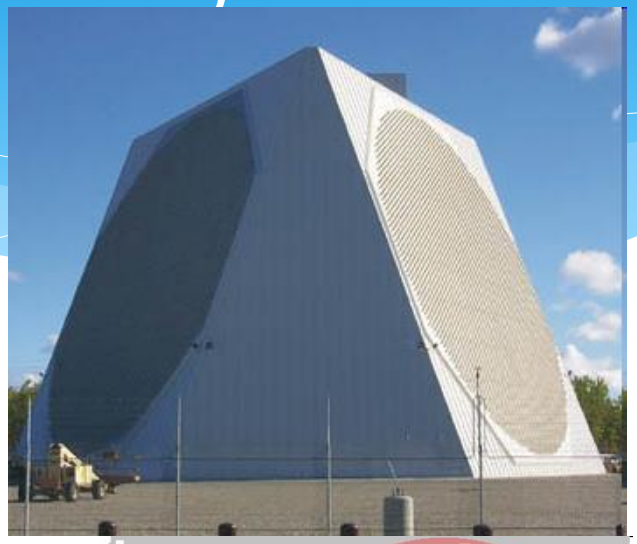
Advantages-Interference Suppression

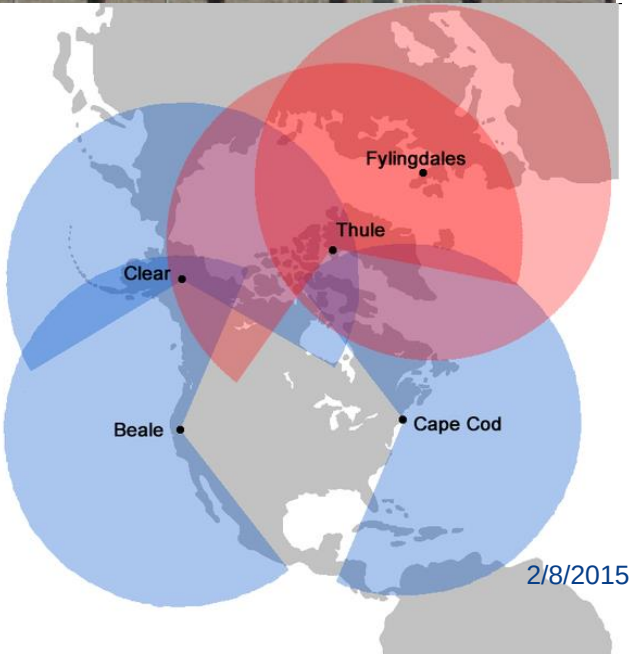


Famous Phased Arrays

* Pave Paws (**P**hased **A**rray **W**arning **S**ystem)
  * Missile warning and space surveillance
  * detecting and tracking Earth-orbiting satellites

  * Elevation coverage 3 to 85 deg
  * Azimuth coverage 120 per face
  * radars is housed in a 32-meter (105-foot) high building
  * 1,792 active elements at 325 watts = 582.4 kilowat (kW)
  * Beamwidth: 2.2 deg
  * Effective Gain 37.92 dB ?
  * Frequency 435 MHz





Patriot

* **SAM**
* **MPQ-53 C-Band** radar
* Multifunctional phased array radar system
* searching, detection, tracking and identification of potential threats, and Patriot missiles guidance and ECCM functions.
* It is able to track more than **100 potential targets** and to engage up to 9 of them.
* The radar system has a range in excess of 100 kilometers.

Real World Example

* Airborne Warning and Control System (AWACS)
  * Flown on top of a U.S. military aircraft
  * Contains an array of 4,000 waveguide slots
  * Ultra-low side lobes that are below -40 dB
  * Provides position and tracking information on enemy aircraft and ships, and location and status of friendly aircraft and naval vessels

AWACS

Perspective

Advantages	Disadvantages
High gain / low side lobes	Very complex
Fast beam jumping	High cost
Computer controlled beam agility	
Single element fault retains operability	

Phased Array Applications

A system not an antenna
5 Decades of service
Military & civil applications

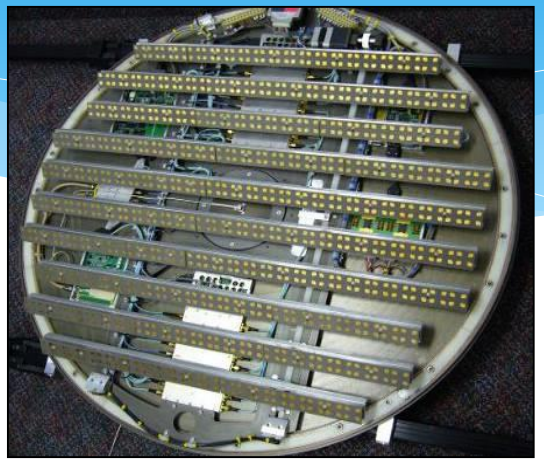
Surveillance
Target Tracking
Missile Guidance
Target Identification
Multi-function System
ECM, ECCM

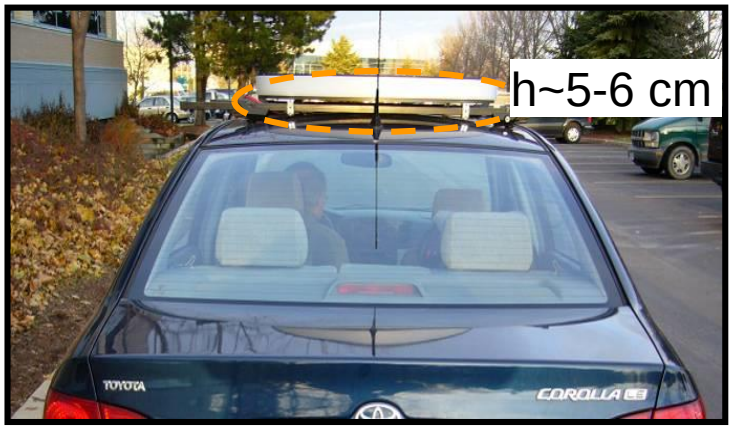
Civil Applications:

Air Traffic Control
Mobile Satellite Systems
Imaging
Radio Astronomy
Smart Antenna for WLAN or Cellular networks
Millimeter-wave wireless networks

Mobile Satellite Systems

- Conformal and Flexible
- Low Profile
- Signal Processing Power



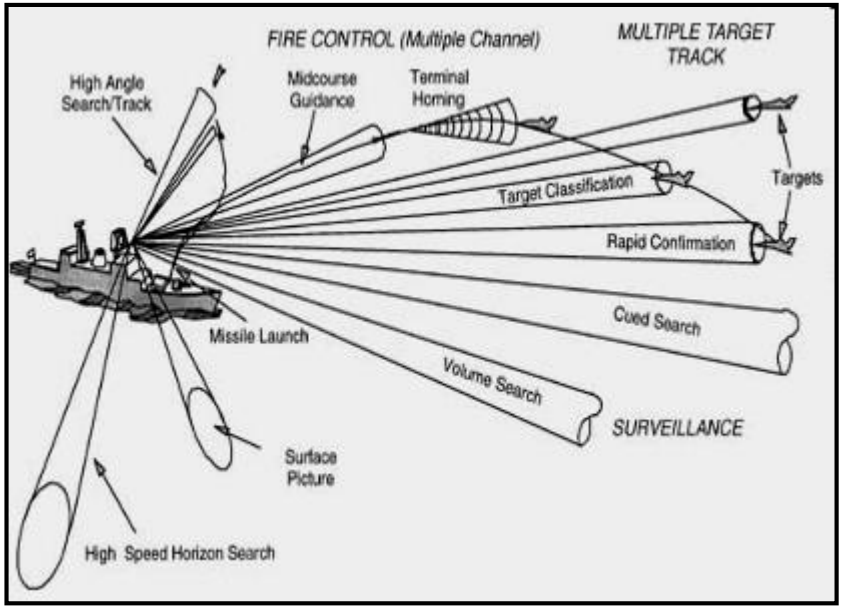


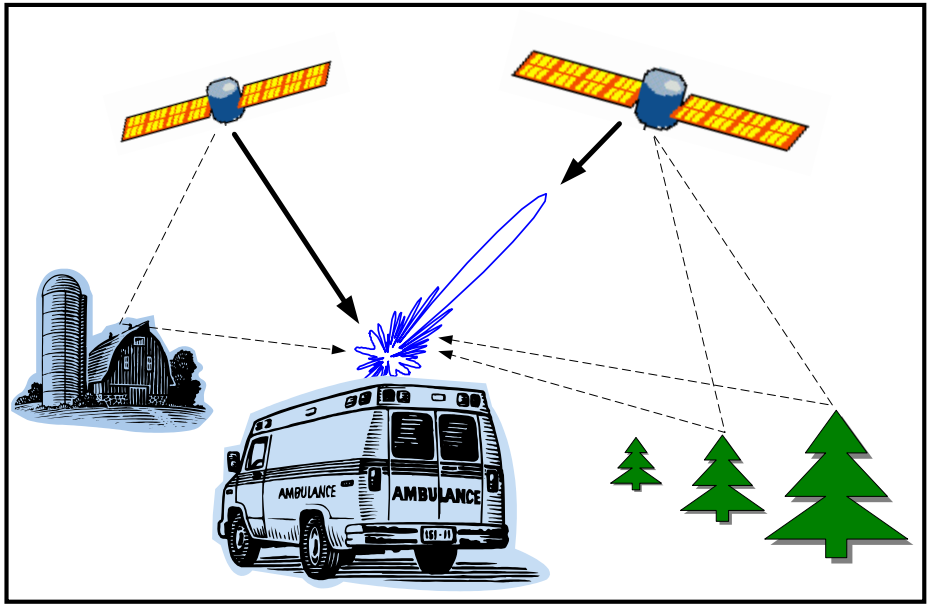
Mobile Ku-band Satellite Rx
Developed at Intelwaves Technologies – University of Waterloo, Canada

Phased Array Aopplications (2)

Agile or Shaped Beam

Multifunction Radar Interference Cancellation

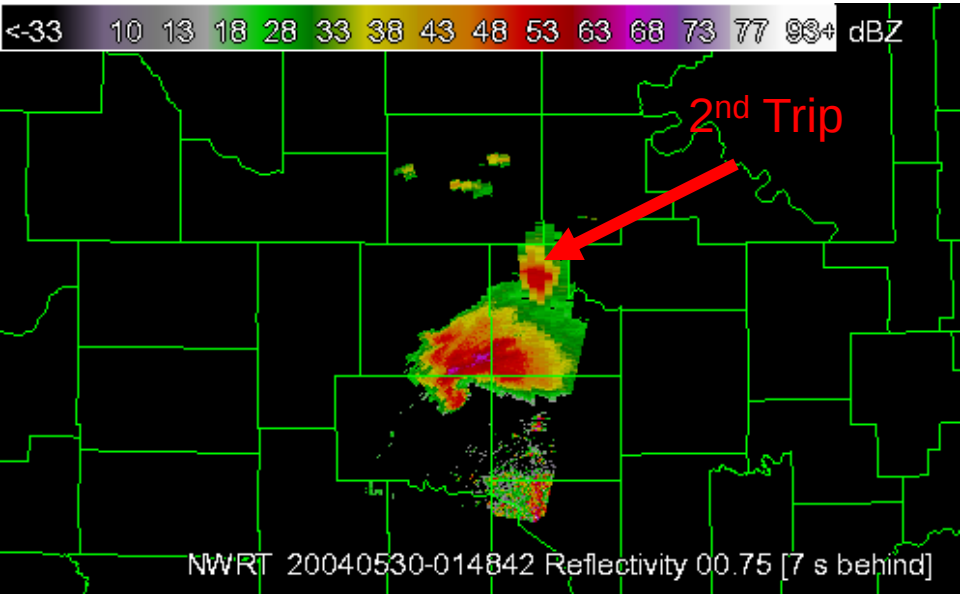




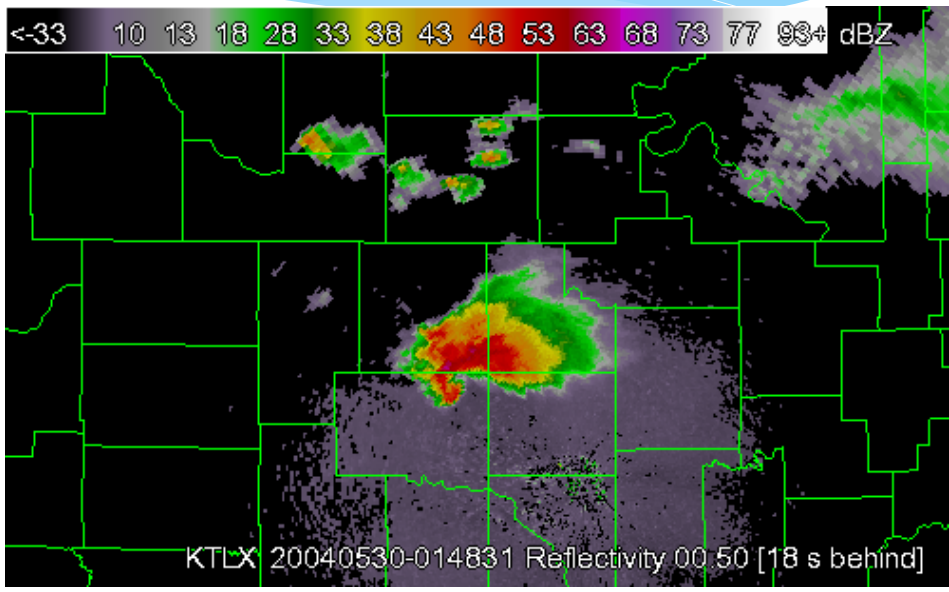
Phased array provides a high Effective Isotropic Radiated Power (EIRP)

NEXRAD-PAR Reflectivity Comparison

NWRT
Phased Array Radar



KTLX
WSR-88D

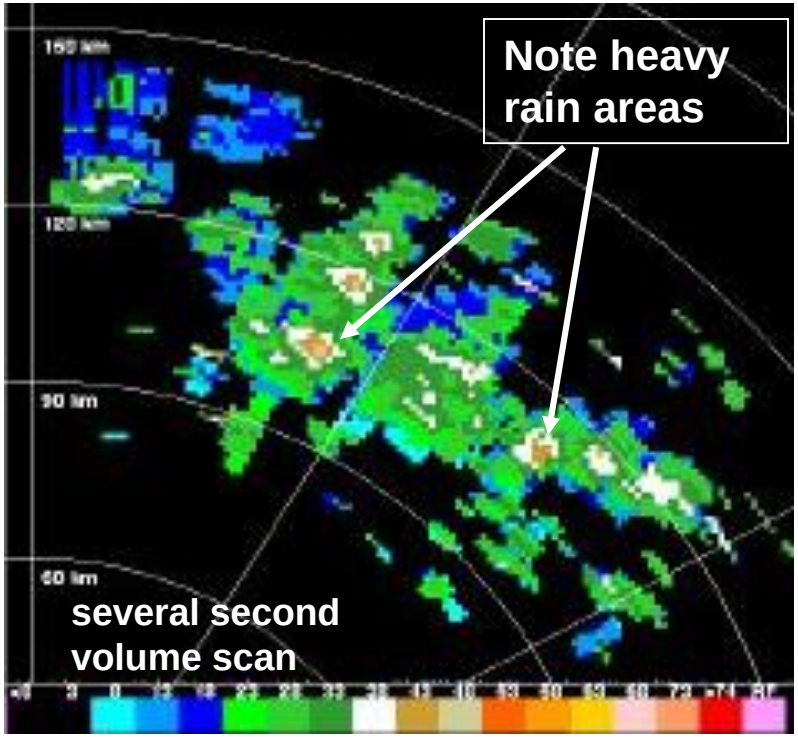


NWRT Volume Scan in less than 1 min.

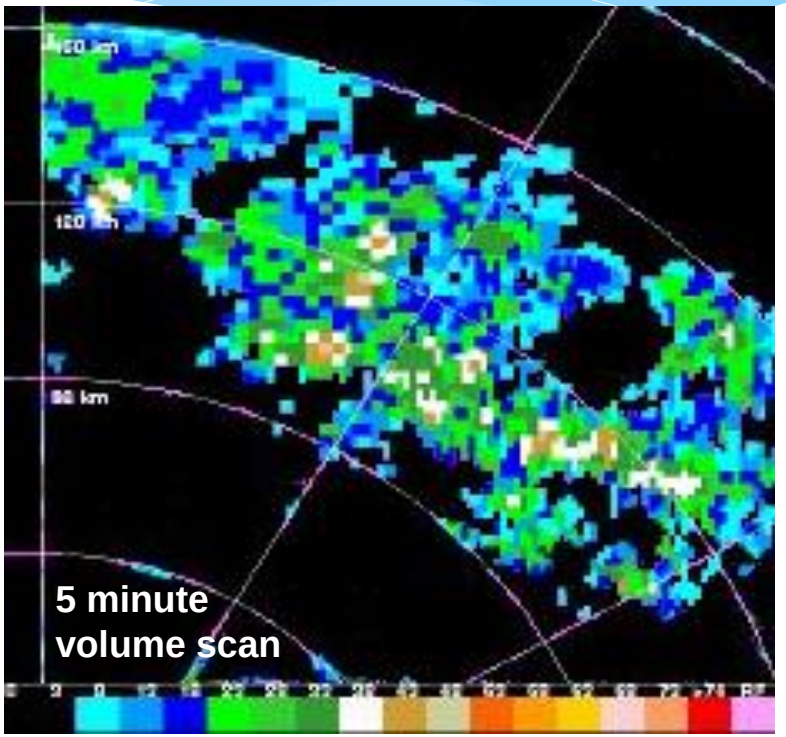
KTLX Volume Scan took 4.2 mins.

Composite Reflectivity: SPY-1 v. WSR-88D

Hurricane Fran Remnants



SPY-1

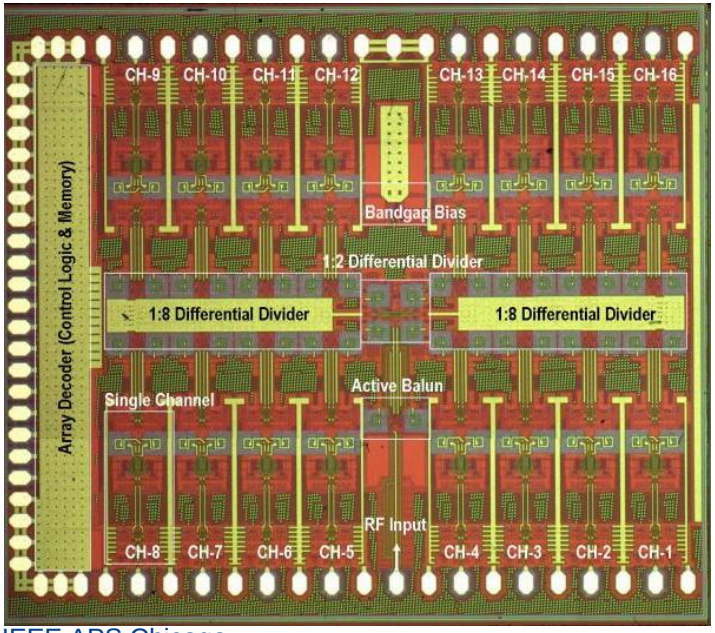


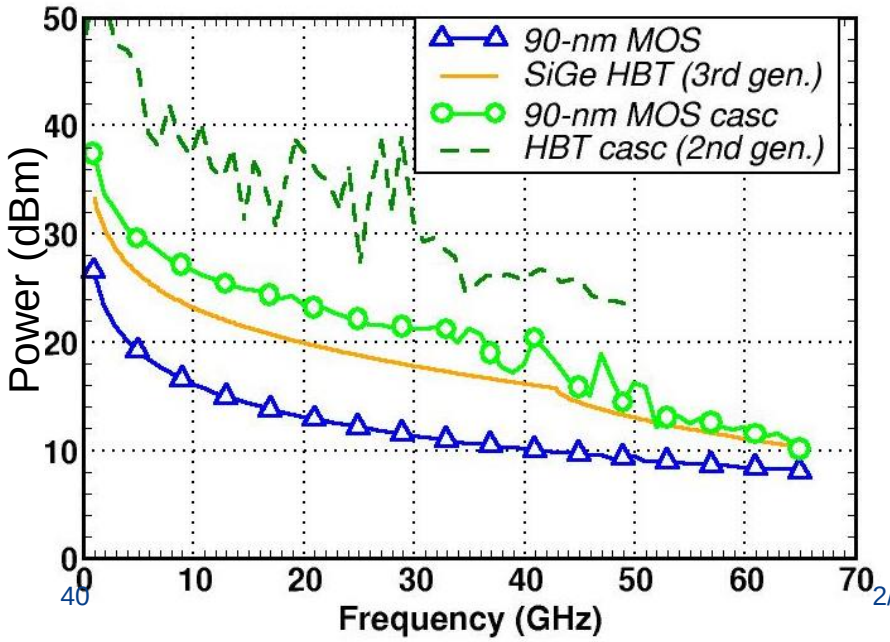
NEXRAD

Spatial Power Combination

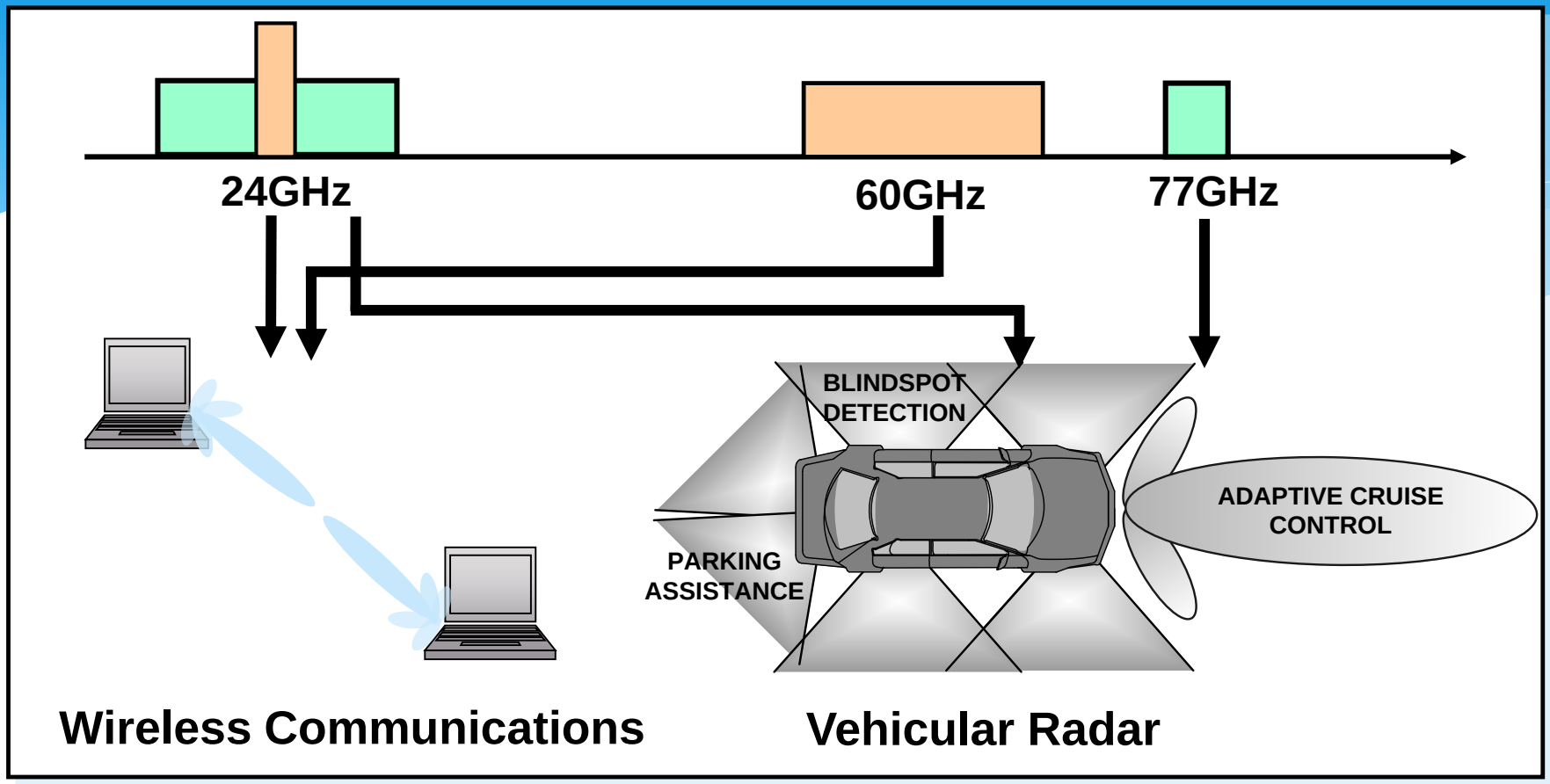
Spatial Power Combination → 20 $\log_{10}$ (*N*)

- CMOS/SiGe Technology
- At mm-wave $P_{out,PA}$<10dBm, G_{LNA}<14dB





Automotive Radar

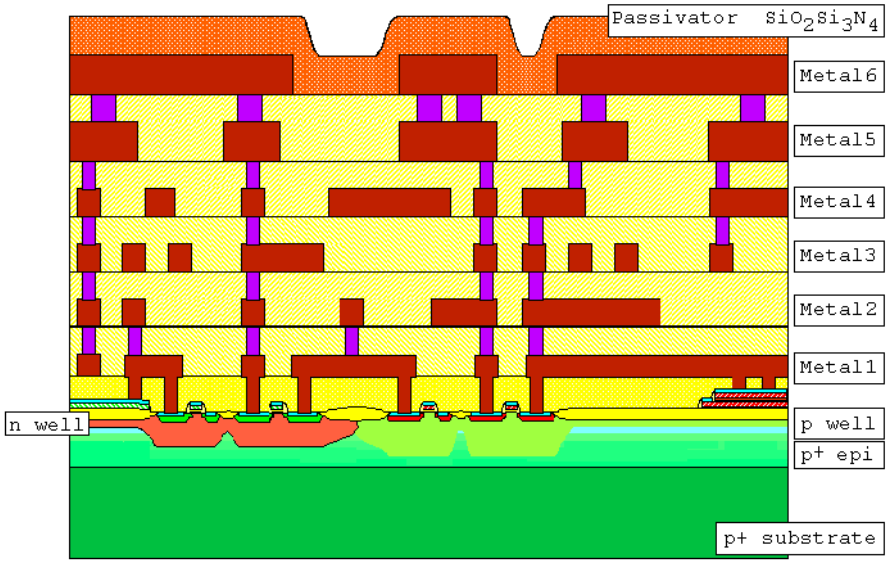


- Fully-integrated silicon-based multiple-antenna systems enable widespread commercial applications at high frequencies.
- Complex, novel architectures can be realized on silicon with greater reliability and lower cost.

Phased Array Drawbacks

* **Cost and Complexity**
* **Bandwidth**
* **Calibration**
* **Beamforming**

CMOS Technology



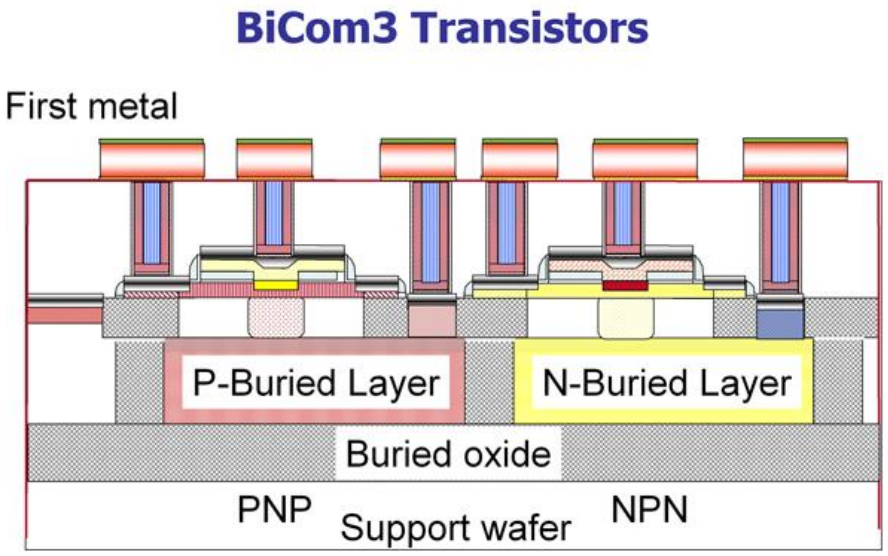


Figure 1. BiCom3 transistors.

Drawbacks of Optimum and Adaptive Beamforming Methods

1) Measuring signal covariance matrix is costly.

2) Direction of Arrival (DOA) of the desired signal is required.

3) Some methods depend on the device characteristics.

4) Platform motion affects the estimated covariance