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***A House of Mirrors: The Indoor Radio Channel and  
Radios for It***

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# ***Outline***

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- **Indoor radio systems: general overview**
- **The indoor radio channel**
- **Radio systems for indoor use:**
  - **802.11 Wireless Local Area Networks**
  - **Bluetooth**
- **The limits of indoor radio communication**
- **Conclusions**

# ***Indoor Radio Systems: An Overview***

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- **The traditional applications of indoor radio systems:**
  - **Cordless telephones**
  - **Remote controls (e.g., garage door openers)**
  - **Baby monitors**
- **The emerging applications:**
  - **Home networking for security and control**
  - **Wireless access to high speed data networks**
  - **Wireless connection of home entertainment systems**

# ***Indoor Radio Systems: An Overview***

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**The new applications of indoor radio systems are characterized by their data rates:**

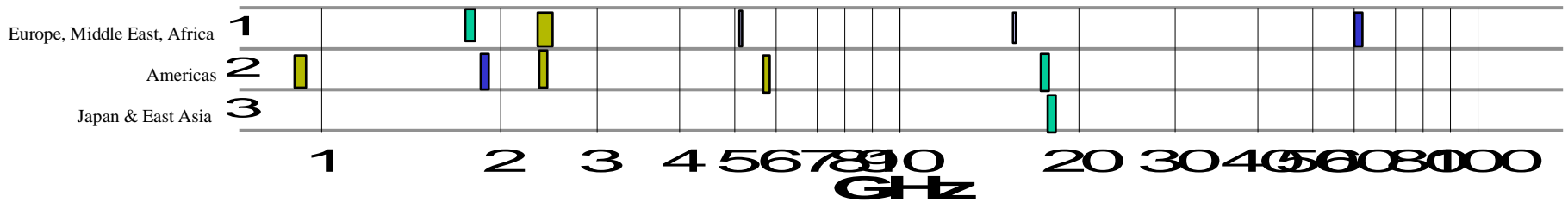
**Home networking, appliance interconnection, security and utilities control: 10 bps to 100 kbps**

**Wireless access to data networks: 1 Mbps to 11 Mbps (now); 56 Mbps and above in two years.**

**Wireless interconnection of home entertainment equipment (“wireless multimedia): 30 Mbps to 400 Mbps.**

# Indoor Radio Propagation

## The frequency bands of interest:



**902 - 928 MHz (US only; used for GSM in Europe)**

**1.910 – 1.920 (US only; unlicensed PCS data band)**

**2.400 – 2.4835 GHz (US ISM, Japan)**

**2.400 – 2.500 GHz (European unlicensed band)**

**5.150 – 5.250 GHz (European HIPERLAN)**

**5.725 – 5.875 GHz (US ISM)**

**61 – 61.5 GHz (Europe)**

# ***Indoor Radio Propagation***

## **The inescapable facts of life:**

**1. Transmission through a wall costs from 3 to 20 dB in signal strength, depending on the construction of the wall. 6 to 10 dB is typical at 2.5 GHz. Loss increases with frequency: at 5 GHz walls usually cost more than 10 dB and at 60 GHz they are essentially opaque.**

**2. Received signal strength falls as  $1/r^3$  to  $1/r^4$ . In commercial space, e.g., supermarkets, we have measured  $1/r^{3.8}$  at 2.5 GHz. Residences are probably not too different.**

**3. Delay spreads are in the range of a few tens of nanoseconds to over a thousand, with short delay spreads being typical for residential and office environments.**

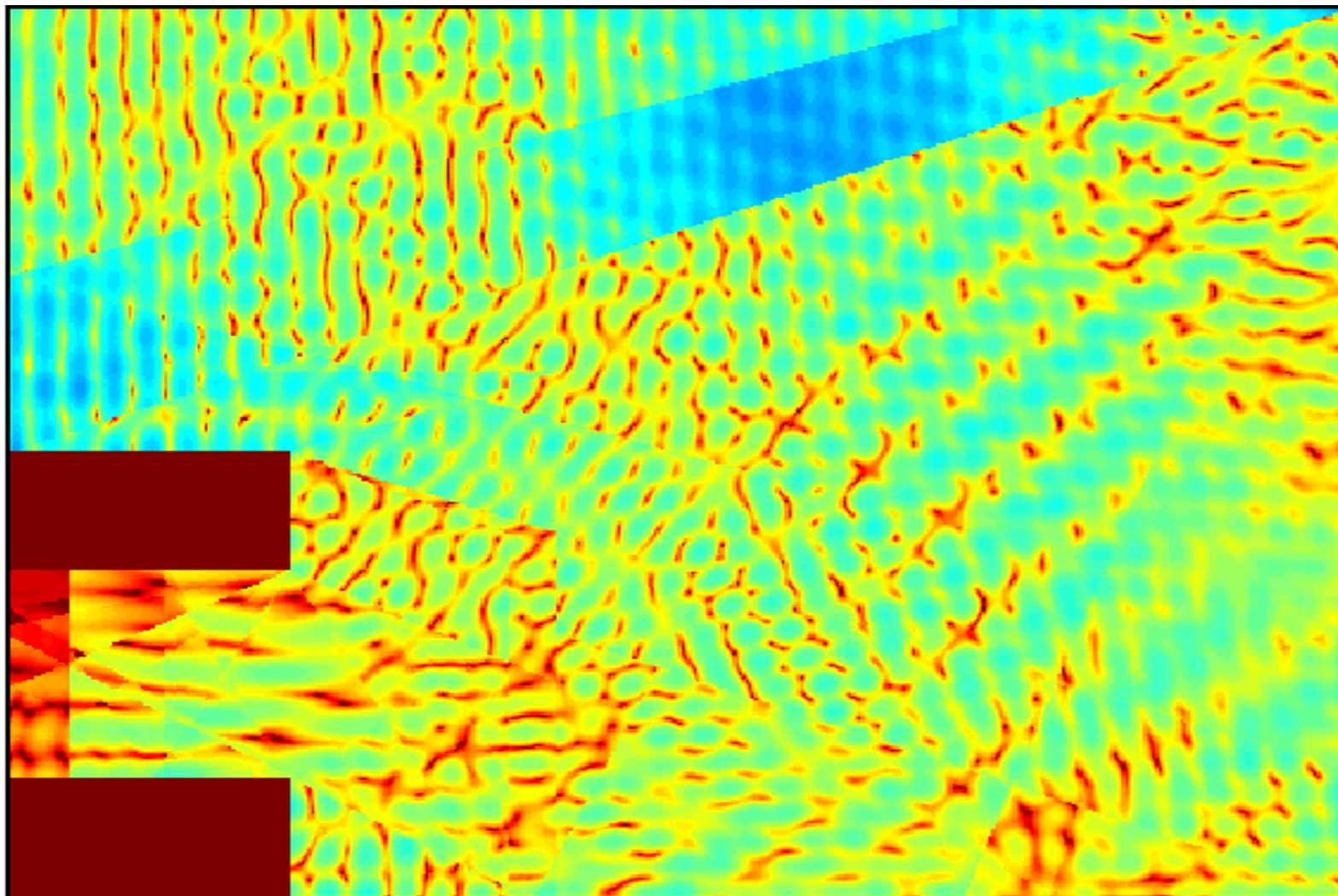
# ***Indoor Radio Propagation***

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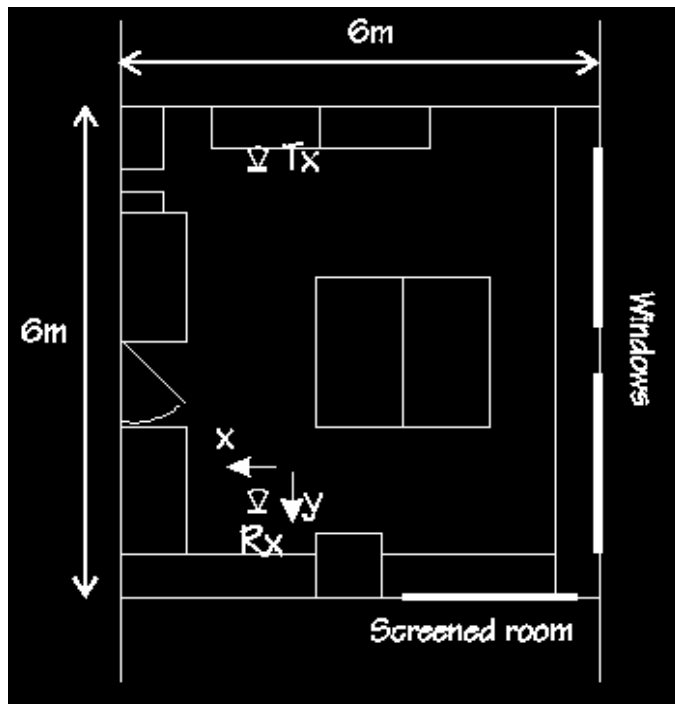
## **More facts of life:**

- 4. At 2.5 GHz, the channel coherence time is several hundred milliseconds to a few seconds, depending on the environment.**
- 5. At 2.5 GHz, the spatial coherence length is about 10 cm, and this doesn't seem to be as variable as the coherence time.**

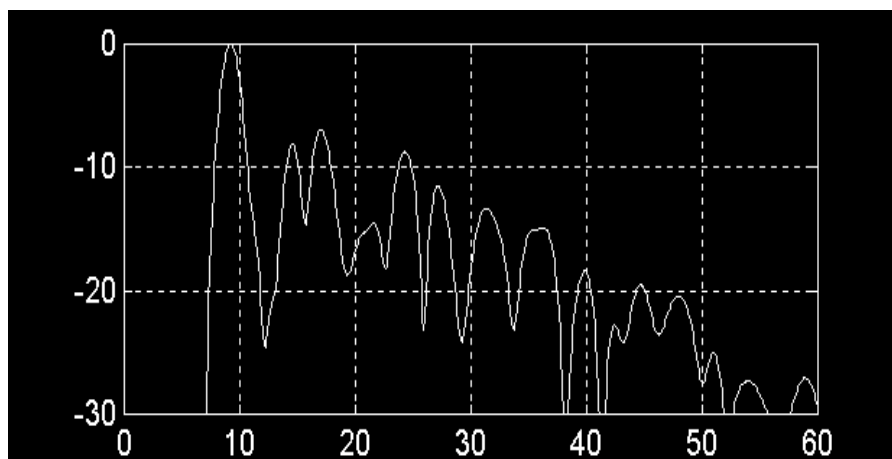
# *Indoor Radio Propagation: Simulation*



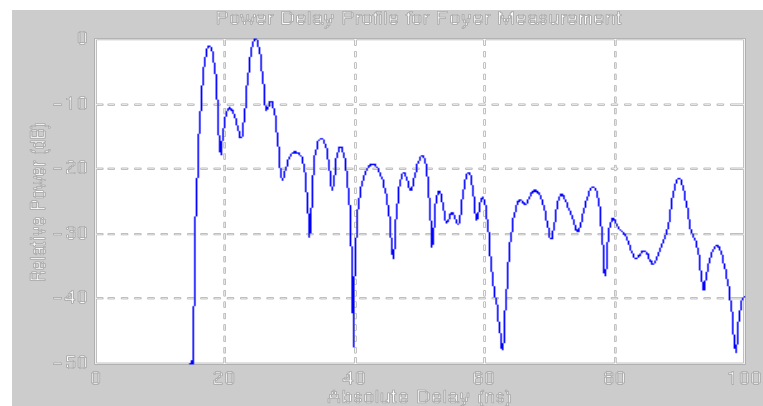
# Indoor Radio Propagation: Measurements



# Indoor Radio Propagation: Measurements



# More Measurements



# ***Radios for the Indoor Channel***

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**I will mostly concentrate on radios for IEEE 802.11 wireless LANs. These are typical of the most widely deployed indoor wireless data systems.**

**I will also describe briefly the Bluetooth standard, principally to show how it differs from 802.11.**

## **The high level requirements:**

**A wireless network meeting the reliability requirements of Ethernet/IEEE 802.3 with the following exceptions:**

**1. The MAC Service Data Unit (MSDU) loss rate shall be less than  $4 \times 10^{-5}$  for an MSDU length of 512 octets.**

**2. The above will be met 99.9 % of the time on a daily basis in 99.9 % of the service area.**

# **Three PHYs**

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- **Frequency Hop Spread Spectrum**
  - 2.4 GHz band, 1 and 2 Mbps transmission
  - 2GFSK, 4GFSK
  - hop over 79 channels (North America)
- **Direct Sequence Spread Spectrum**
  - 2.4 GHz band, 1 and 2 Mbps transmission
  - DBPSK, DQPSK
  - 11 chip Barker sequence
- **Baseband IR**
  - Diffuse infrared
  - 1 and 2 Mbps transmission, 16-PPM and 4-PPM

**I'll mostly be describing the direct sequence spread spectrum PHY layer, since that is the dominant in interoperable systems.**

**Frequency hopped system are still common, but as radios integrated into systems such as bar code scanners. They are not common in wireless LAN equipment.**

# ***IEEE 802.11 DSSS PHY characteristics***

- **2.4 GHz ISM band (FCC 15.247)**
- **1 and 2 Mb/s data rate (DBPSK and DQPSK modulation)**
- **Symbol rate 1MHz**
- **Chipping rate 11 MHz with 11 chip Barker sequence**
- **Multiple channels in 2.4 to 2.4835 GHz band**
- **The system uses Time Division Duplexing (TDD)**
- **Multiple access is by Carrier Sense (called Clear Channel Assessment)/Collision Avoidance with explicit acknowledgment of non-broadcast frames.**

# DSSS Specification Summary

- Slot time 20  $\mu\text{s}$
- TX to Rx turnaround time 10  $\mu\text{s}$
- Rx to Tx turnaround time 5  $\mu\text{s}$
- Operating temperature range
  - type 1: 0 - 40 °C
  - type 2: -30 - 70 °C
- Tx Power Levels
  - 1000 mW USA
  - 100 mW Europe
  - 10 mW/MHz Japan
- Minimum Transmitted Power 1 mW
- Tx power level control required above 100 mW

# DSSS Specification Summary (cont)

- Tx Center Frequency Tolerance                    +/- 25 ppm
- Chip Clock Frequency Tolerance                +/- 25 ppm
- Tx Power On Ramp                                2  $\mu$ s
- Tx Power Down Ramp                            2  $\mu$ s
- RF Carrier suppression                        15 dB
- Transmit modulation accuracy                test procedure
- Rx sensitivity                                    -80 dB  
    (@ 0.08FER (1024 Bytes))
- Rx max input level                              -4 dB
- Rx adjacent channel rejection                >35 dB  
    (@ > 30 MHz separation  
    between channels)

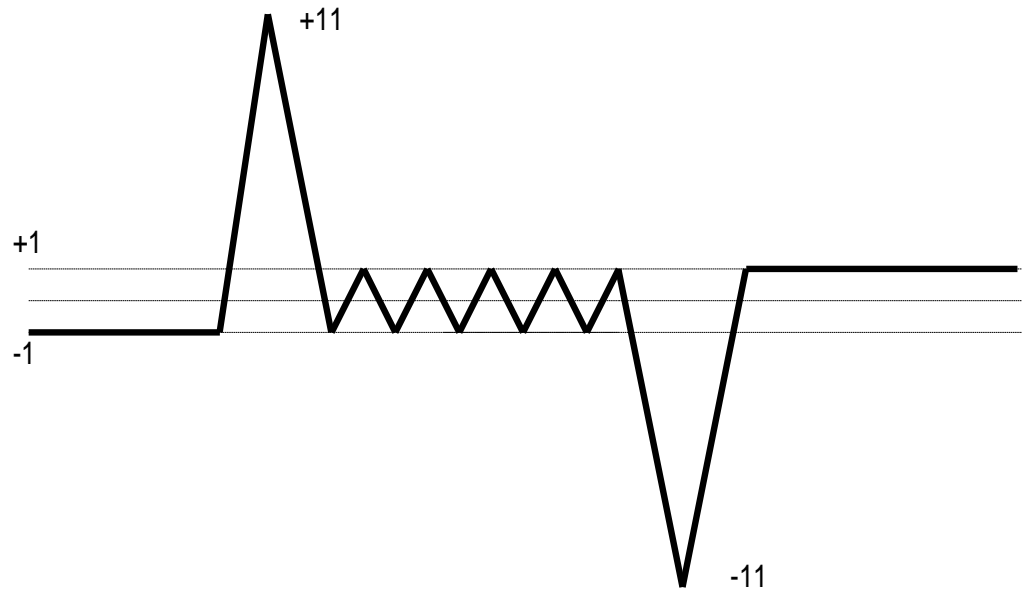
# DSSS Channels

| <b>CHNL_ID</b> | <b>FCC Channel Frequencies</b> | <b>ETSI Channel Frequencies</b> | <b>Japan Frequency</b> |
|----------------|--------------------------------|---------------------------------|------------------------|
| 1              | 2412 MHz                       | N/A                             | N/A                    |
| 2              | 2417 MHz                       | N/A                             | N/A                    |
| 3              | 2422 MHz                       | 2422 MHz                        | N/A                    |
| 4              | 2427 MHz                       | 2427 MHz                        | N/A                    |
| 5              | 2432 MHz                       | 2432 MHz                        | N/A                    |
| 6              | 2437 MHz                       | 2437 MHz                        | N/A                    |
| 7              | 2442 MHz                       | 2442 MHz                        | N/A                    |
| 8              | 2447 MHz                       | 2447 MHz                        | N/A                    |
| 9              | 2452 MHz                       | 2452 MHz                        | N/A                    |
| 10             | 2457 MHz                       | 2457 MHz                        | N/A                    |
| 11             | 2462 MHz                       | 2462 MHz                        | N/A                    |
| 12             | N/A                            | N/A                             | 2484 MHz               |

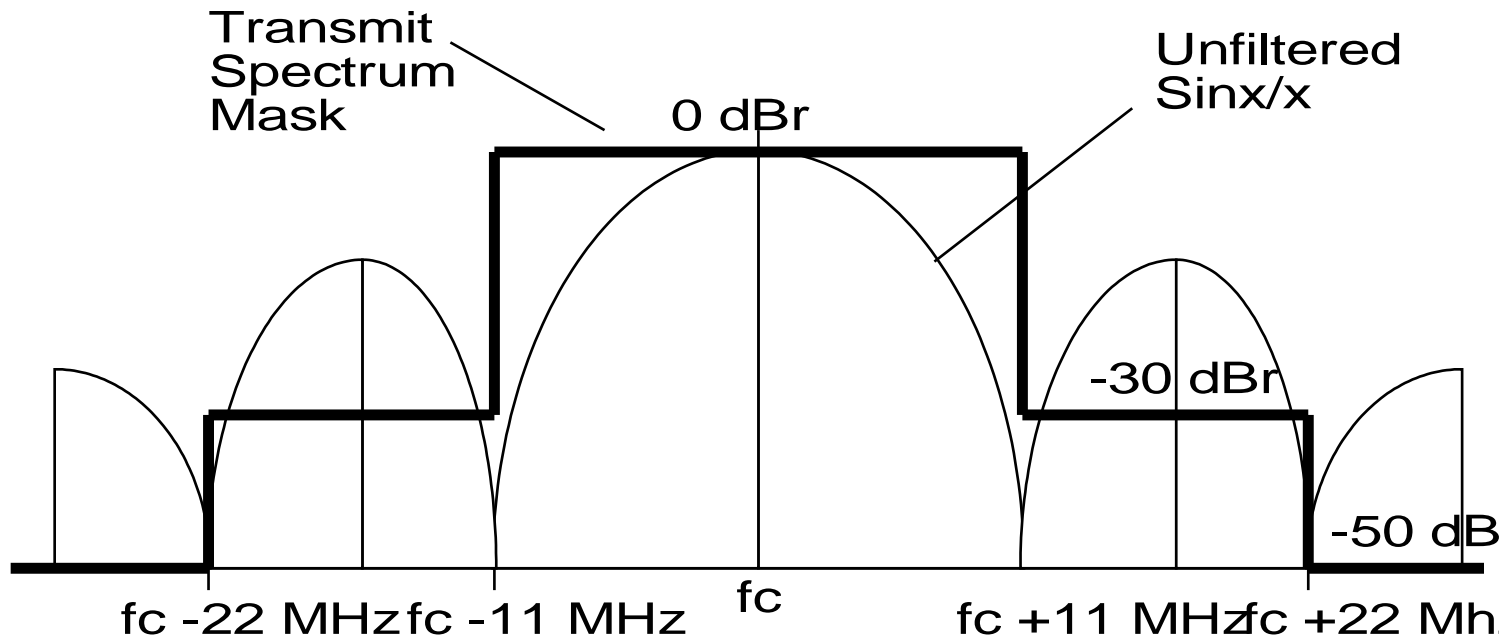
**Table 1, DSSS PHY Frequency Channel Plan**

# 11 chip BARKER sequence

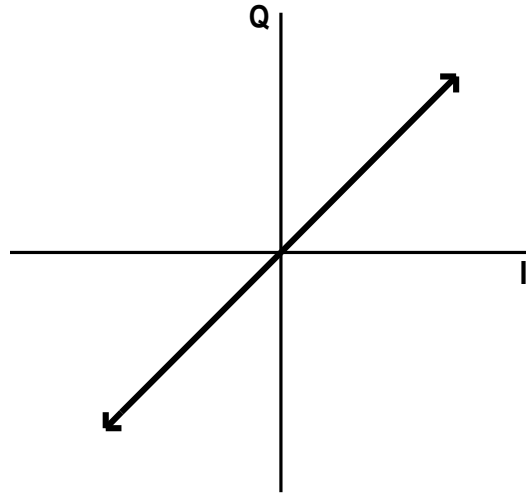
- Good autocorrelation properties
- Minimal sequence allowed by FCC
- Coding gain 10.4 dB



# Transmit Spectrum Mask



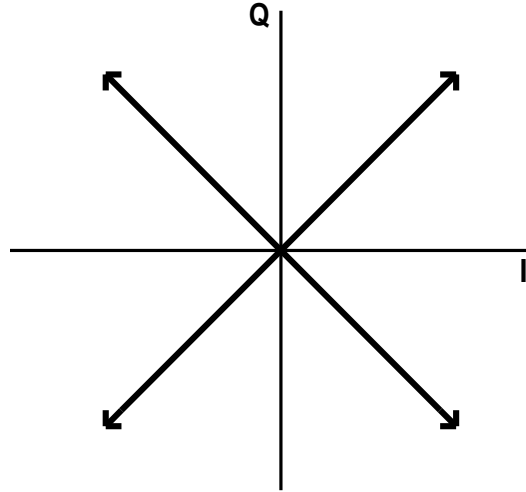
# DBPSK Modulation



| Bit Input | Phase Change ( $+j\omega$ ) |
|-----------|-----------------------------|
| 0         | 0                           |
| 1         | $\pi$                       |

Table 1, 1 Mb/s DBPSK Encoding Table.

# DQPSK Modulation



| Dibit pattern (d0,d1)<br>d0 is first in time | Phase Change (+j $\omega$ ) |
|--|-----------------------------|
| 00   | 0                           |
| 01   | $\pi/2$                     |
| 11   | $\pi$                       |
| 10   | $3\pi/2$ ( $-\pi/2$ )       |

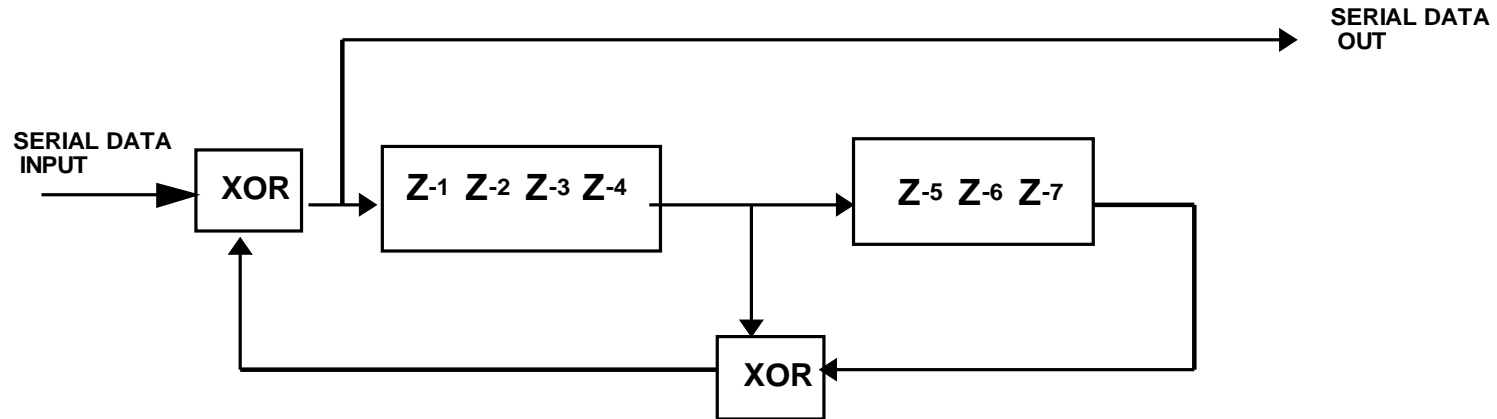
Table 1, 2 Mb/s DQPSK Encoding Table

# Clear Channel Assessment

- **Three methods:**
  - **CCA mode 1: Energy above threshold**
  - **CCA mode 2: Carrier sense only**
  - **CCA mode 3: Carrier sense with energy above threshold**
- **Energy detection function of TX power**
  - **Tx power > 100 mW: -80 dBm**
  - **Tx power > 50mW : -76 dBm**
  - **Tx power < = 50mW: -70 dBm**
- **Energy detect time : 15  $\mu$ s**
- **Correct PLCP header --> CCA busy for full (intended) duration of of frame as indicated by PLCP Length field**

# Data Scrambler

Scrambler Polynomial;  $G(z)=Z^{-7} + Z^{-4} + 1$

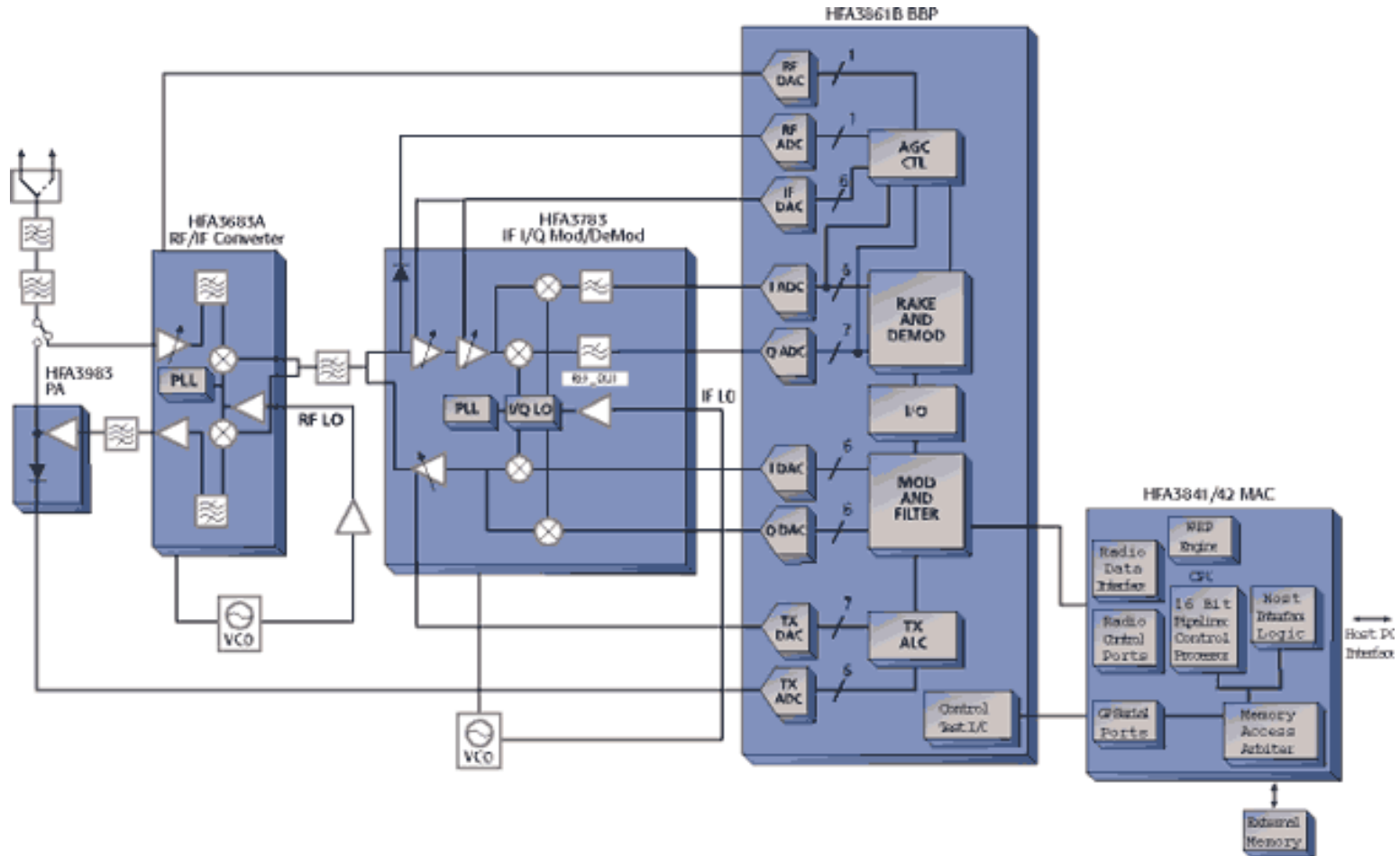


- **ALL** bits transmitted by the DSSS PHY are scrambled
- **Purpose**
  - Whitening the spectrum
  - DC blocking (Barker sequence is asymmetric)

# Receiver Performance Specifications

| <u>Parameter</u>                  | <u>1 Mb/s</u>  | <u>2 Mb/s</u>  |
|-----------------------------------|----------------|----------------|
| <b>Sensitivity</b>                | <b>-80 dBm</b> | <b>-75 dBm</b> |
| <b>Desensitization</b>            |                |                |
| <b>@ 2 MHz offset</b>             | <b>30 dB</b>   | <b>40 dB</b>   |
| <b>@ 3 MHz or more</b>            | <b>20 dB</b>   | <b>30 dB</b>   |
| <b>Intermodulation Protection</b> | <b>30 dB</b>   | <b>25 dB</b>   |

# Intersil PRISM II chipset for 802.11



# ***Intersil PRISM II chipset for 802.11***

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## **Front end radio specifications:**

**Rx:**

**Noise Figure 3.7 dB**

**Gain 25 dB**

**Input IP3 -13 dBm**

**Tx:**

**Output power +17 dBm (at -1 dB compression)**

## ***Intersil PRISM II chipset for 802.11***

**The PRISM II chipset is implemented using a SiGe add-on to an existing CMOS process. This is new. Most 802.11 RF chipsets have been based on bipolar technology.**

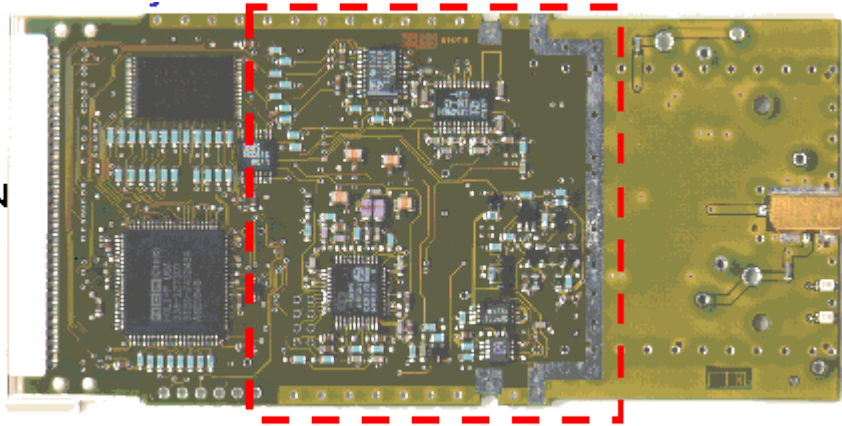
**There are still some 2.4 GHz components implemented in GaAs available, but this will probably change over the next three years as SiGe (and finally RF CMOS) start to be common.**

**At 5 GHz, GaAs is still the only choice. CMOS (even SiGe) still has a long way to go.**

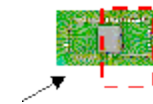
**In the millimeter wave, GaAs or even InP are needed to get decent performance.**

# Future 802.11 Radio Evolution

2.4 GHz  
WaveLAN



Single chip CMOS  
Radio prototype for  
802.11



5.2 GHz  
Prototype

# ***Other Indoor Radio Technologies***

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## **Home RF:**

**This is an evolving standard being pushed by a group of companies led by Intel. It is very similar to 802.11, but with a maximum transmit power of +20 dBm, and relaxed RF specifications. It also adds an isochronous transport mode to support cordless telephony.**

## **Bluetooth:**

**This standard was originally designed to displace IR links for very short range (3 m) data links. Extensions are being developed to make it competitive with Home RF.**

**Bluetooth has received lots of publicity since its sponsors promised single chip CMOS transceivers for \$5 apiece.**

# **Bluetooth**

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## **Radio Specifications:**

### **Rx:**

**-70 dBm sensitivity at  $10^{-3}$  BER**

**-20 dBm maximum signal strength at  $10^{-3}$  BER**

### **Tx:**

**0 dBm output power (Bluetooth class 3 device)**

**Out of band spurious emissions:**

**-57 dBm 30 MHz to 1 GHz**

**-47 dBm 1 GHz to 12.75 GHz**

**(power measured in 100 kHz bandwidth)**

# **Bluetooth**

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**Bluetooth implements a fast frequency hopping scheme:**

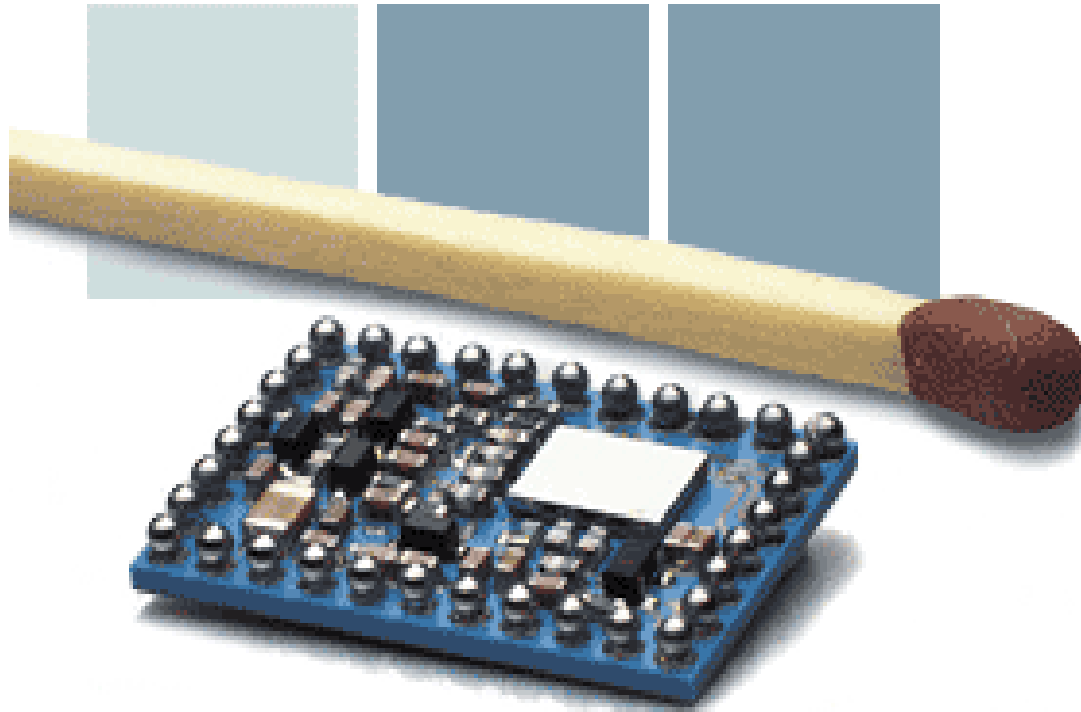
**1600 hops/s**

**Modulation is Gaussian Minimum Shift Keying (constant envelope so works with nonlinear or saturating power amplifiers)**

**Symbol rate is 1 Msymbols/s**

**User data traffic is 434 kbps symmetrical (both uplink and downlink) or 723 kbps/58 kbps asymmetrical. Up to four channels may be configured for isochronous traffic carrying 64 kbps PCM voice.**

# Bluetooth



BiCMOS technology

0 dBm output power

Some filter components  
integrated into 6 layer  
ceramic substrate

VCO requires laser  
trimming to meet frequency  
specification.

Closer to \$30 than \$5.

# ***The Limits of Indoor Wireless***

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**How many bits per second can we send through a band limited channel?**

**As it turns out, more than you might think.**

**In fact, the multipath that we worked so hard avoid can help us!**

# ***Gigabit Indoor Wireless***

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**Experiments performed at AT&T in the early and mid-1990s showed that using directional antennas is possible to transmit hundreds of Mbps to a Gbps at low millimeter wavelength (19 GHz) indoors.**

**Directional antennas were used to control multipath. The system did not even have an equalizer.**

# ***High Throughput Indoor Wireless***

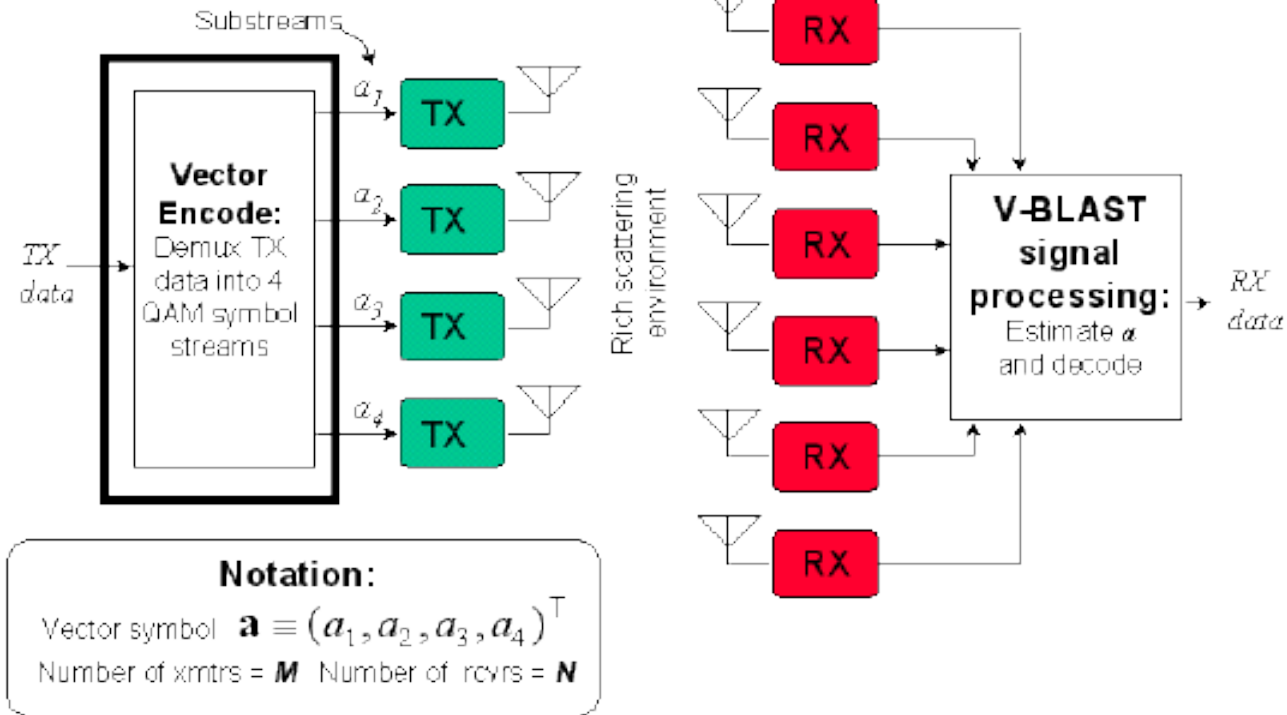
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**A new scheme exploits multipath to increase system capacity, instead of treating it as an impairment to be overcome.**

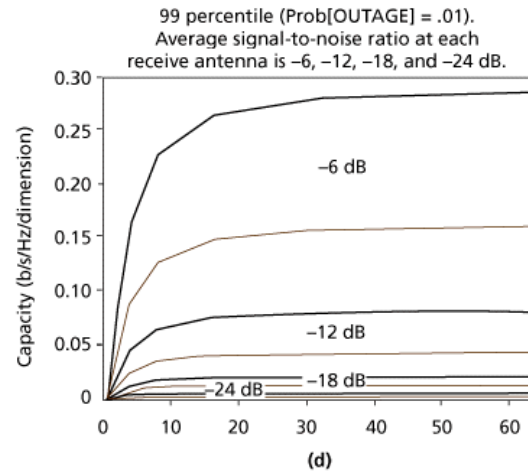
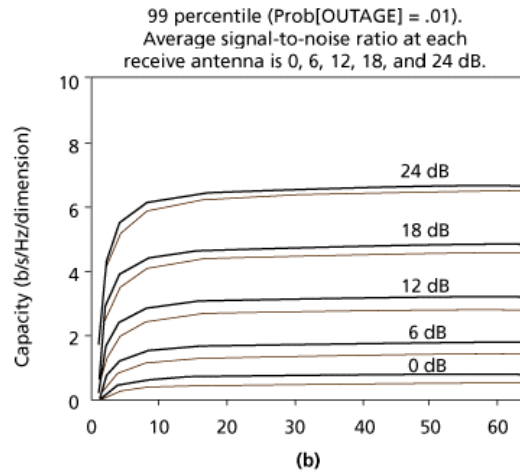
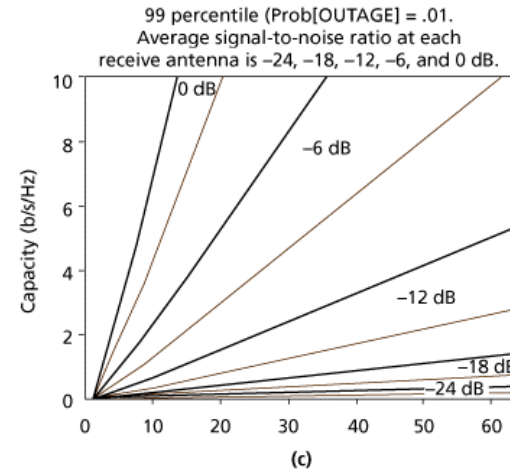
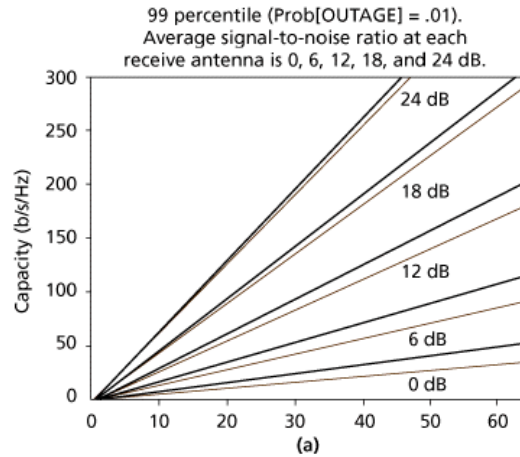
**At Lucent, this is called the BLAST (Bell labs Layered Space Time) architecture.**

**The main drawback of the algorithm is that it requires that your device be big enough to support multiple antennas. (But the Apple I-book already has two antennas built in to support 802.11 wireless networking, so maybe this isn't such a problem.)**

# BLAST



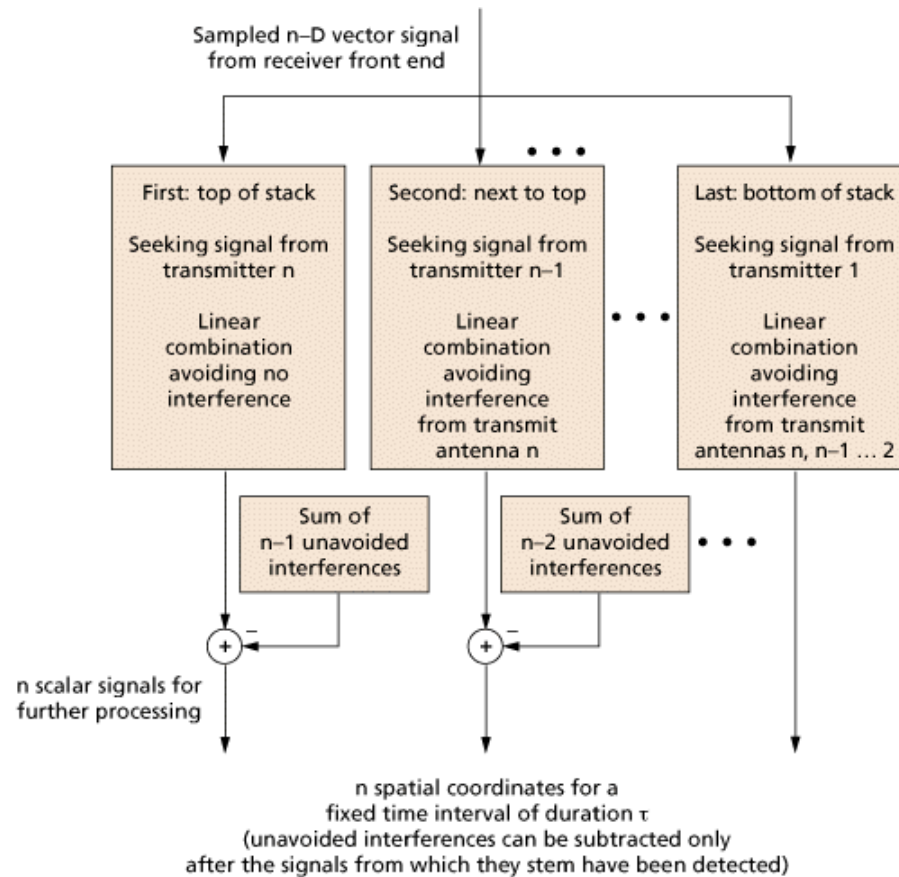
# BLAST



The number of transmit antennas equals the number of receive antennas.

- Capacities
- Capacity lower bounds

# BLAST



# ***Conclusions***

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**The indoor radio channel can be ugly because of its wide angle of arrival spread. However, it is generally not as bad as the outdoor channel in terms of delay spread.**

**Walls are bad for coverage, if you want to cover an indoor space with only a few access points. But walls can help increase overall capacity by isolating adjacent cells. As frequency increases, loss caused by walls gets worse.**

**Cost effective radio technologies are only available for systems operating below 3 GHz. We still need exotic semiconductors at higher frequencies (despite some of our own press releases).**