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

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Outline

- 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

- **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

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

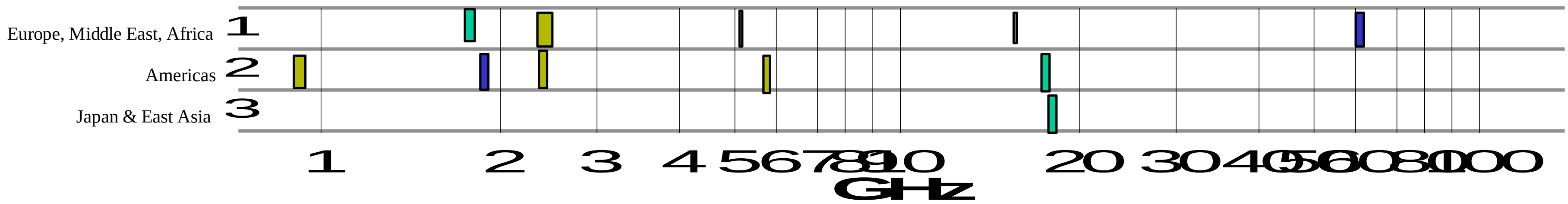
Home networking, appliance interconnection, security and utilities control: 10 bps to 100 kbps

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.

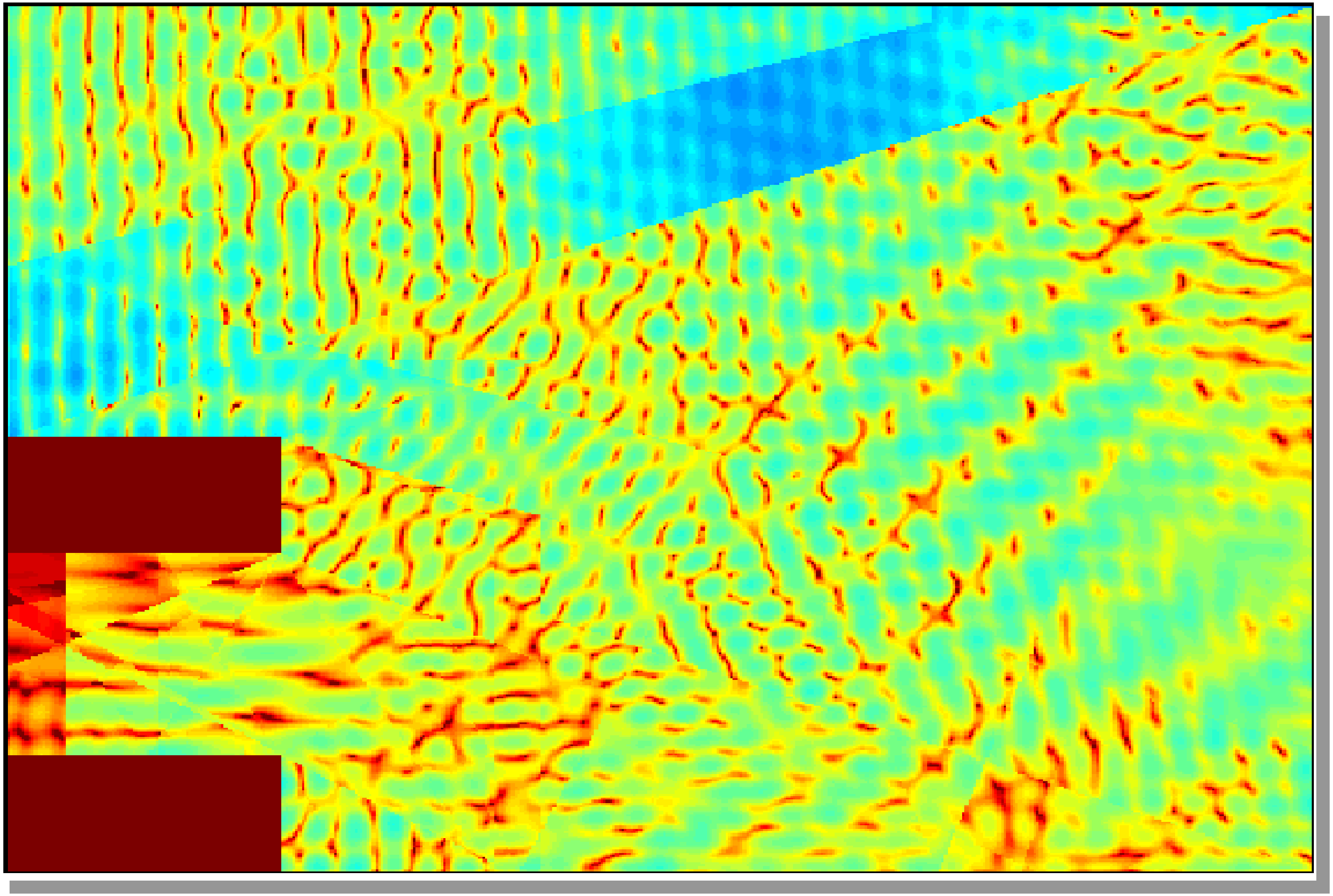
3. Delay spreads are in the range of a few tens of nanoseconds to over a thousand, with short delay spreads being typical for residential and office environments.

More facts of life:

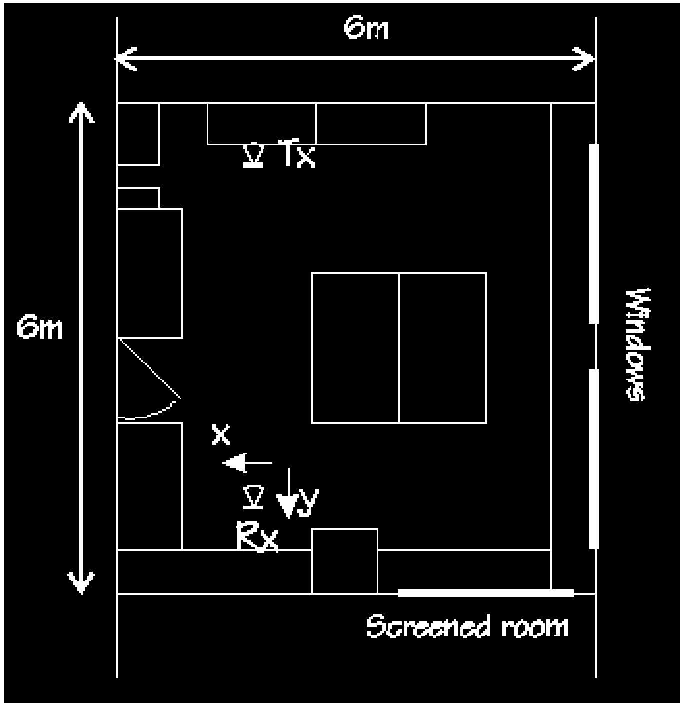
4. At 2.5 GHz, the channel coherence time is several hundred milliseconds to a few seconds, depending on the environment.

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.

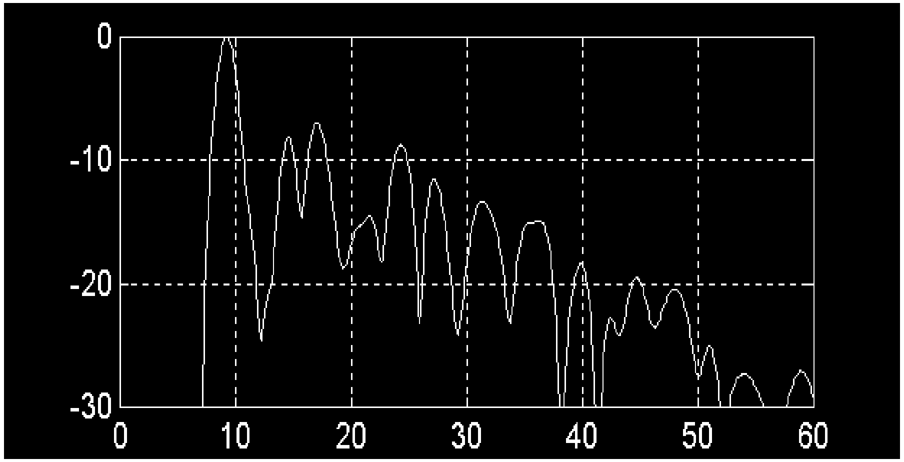
Indoor Radio Propagation: Simulation



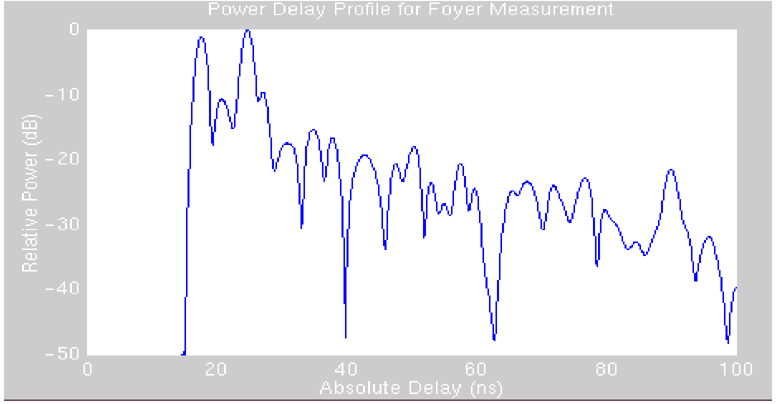
Indoor Radio Propagation: Measurements



Indoor Radio Propagation: Measurements



More Measurements



Radios for the Indoor Channel

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.

IEEE 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 4×10^{-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

- **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**

IEEE 802.11

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** µs
- **TX to Rx turnaround time** **10** µs
- **Rx to Tx turnaround time** **5** µs
- **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** μs
• **Tx Power Down Ramp**	**2** μs
• **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)

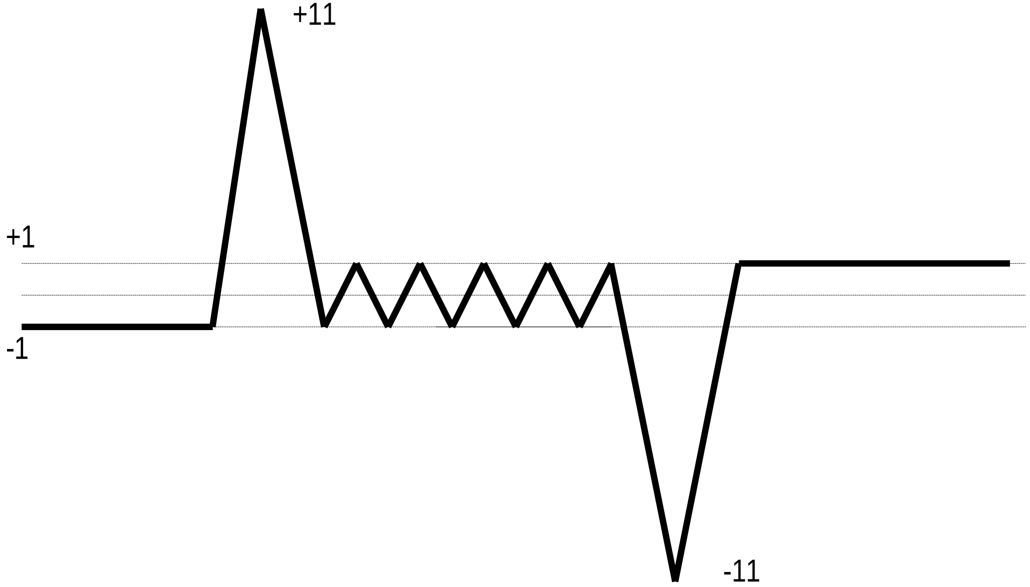
DSSS Channels

CHNL_ID	FCC Channel Frequencies	ETSI Channel Frequencies	Japan Frequency
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

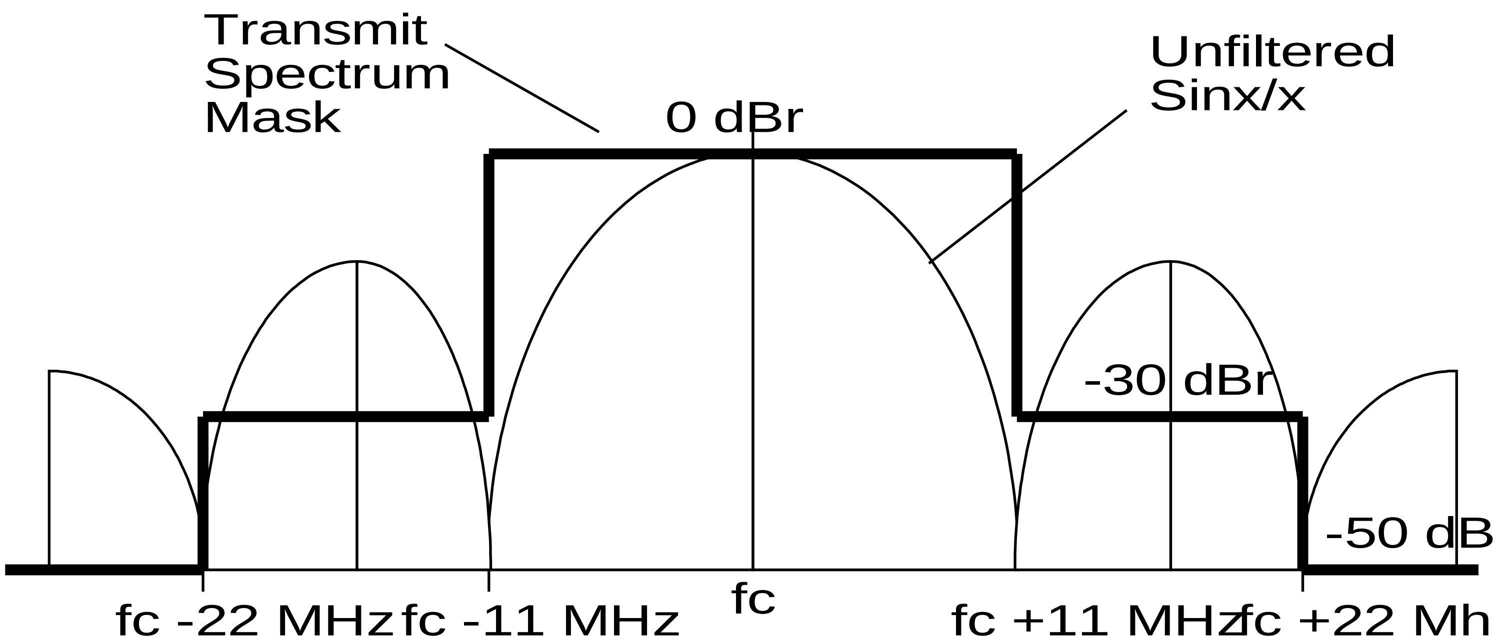
Table 1, DSSS PHY Frequency Channel Plan

11 chip BARKER sequence

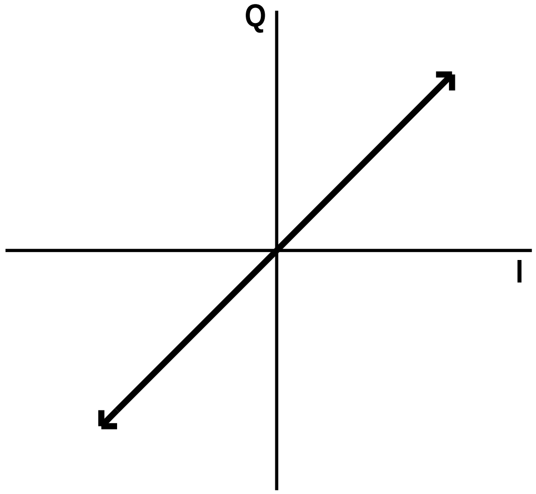
- **Good autocorrelation properties**
- **Minimal sequence allowed by FCC**
- **Coding gain 10.4 dB**



Transmit Spectrum Mask



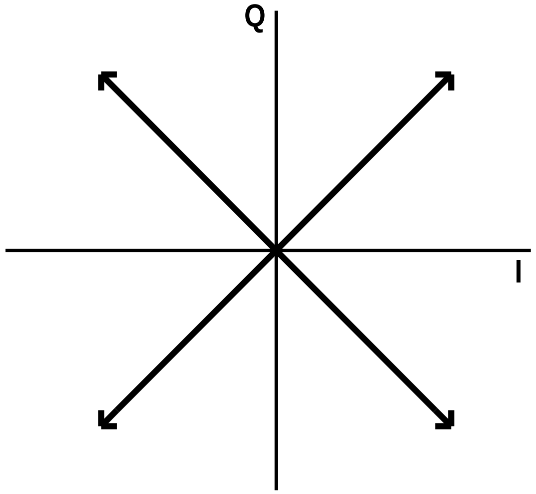
DBPSK Modulation



Bit Input	Phase Change (+jω)
0	0
1	π

Table 1, 1 Mb/s DBPSK Encoding Table.

DQPSK Modulation



Dibit pattern (d0,d1) d0 is first in time	Phase Change (+jω)
00	0
01	$\pi/2$
11	π
10	$3\pi/2$ $(-\pi/2)$

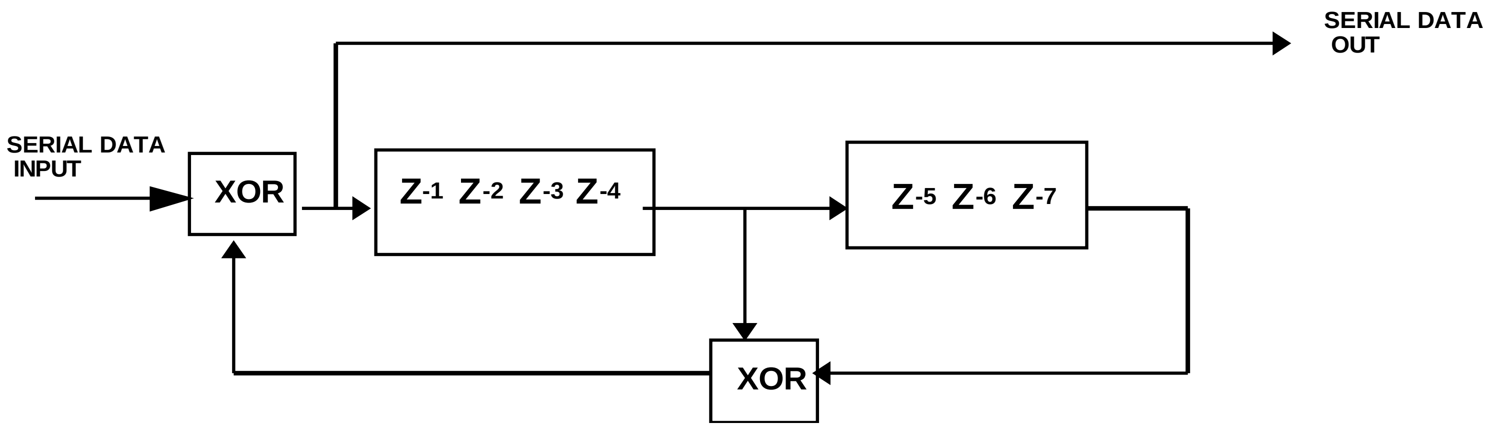
Table 1, 2 Mb/s DQPSK Encoding Table

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** μs
- **Correct PLCP header --> CCA busy for full (intended) duration of of frame as indicated by PLCP Length field**

Data Scrambler

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

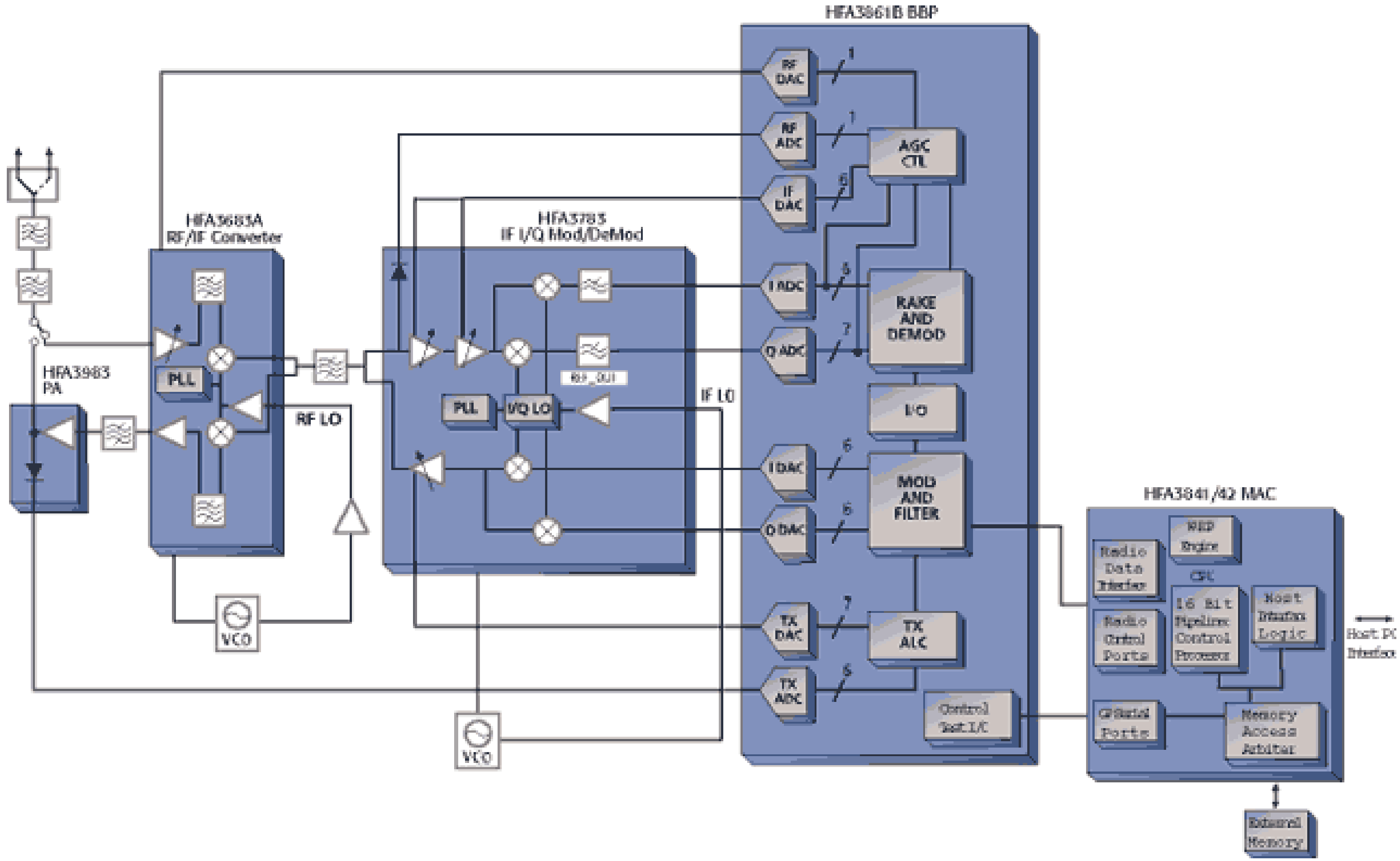


- **ALL bits transmitted by the DSSS PHY are scrambled**
- **Purpose**
  - **Whitening the spectrum**
  - **DC blocking (Barker sequence is asymmetric)**

Receiver Performance Specifications

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

Intersil PRISM II chipset for 802.11



Intersil PRISM II chipset for 802.11

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.

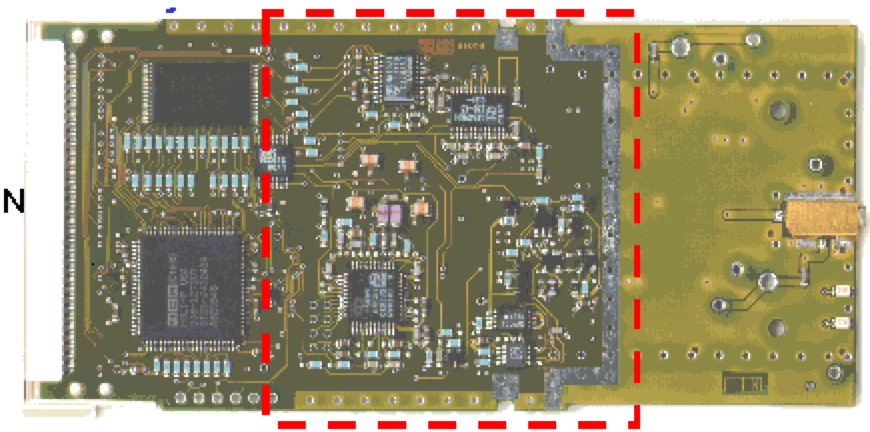
There are still some 2.4 GHz components implemented in GaAs available, but this will probably change over the next three years as SiGe (and finally RF CMOS) start to be common.

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

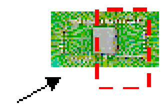
In the millimeter wave, GaAs or even InP are needed to get decent performance.

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

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

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

Bluetooth implements a fast frequency hopping scheme:

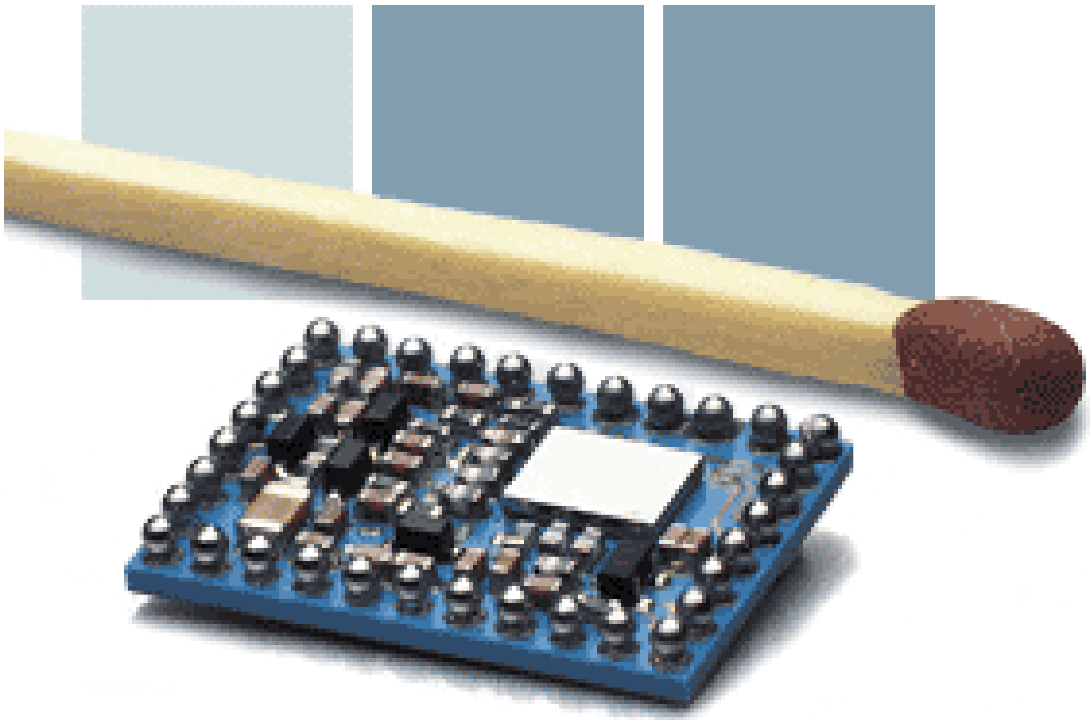
1600 hops/s

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

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

Experiments performed at AT&T in the early and mid-1990s showed that using directional antennas is was 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.

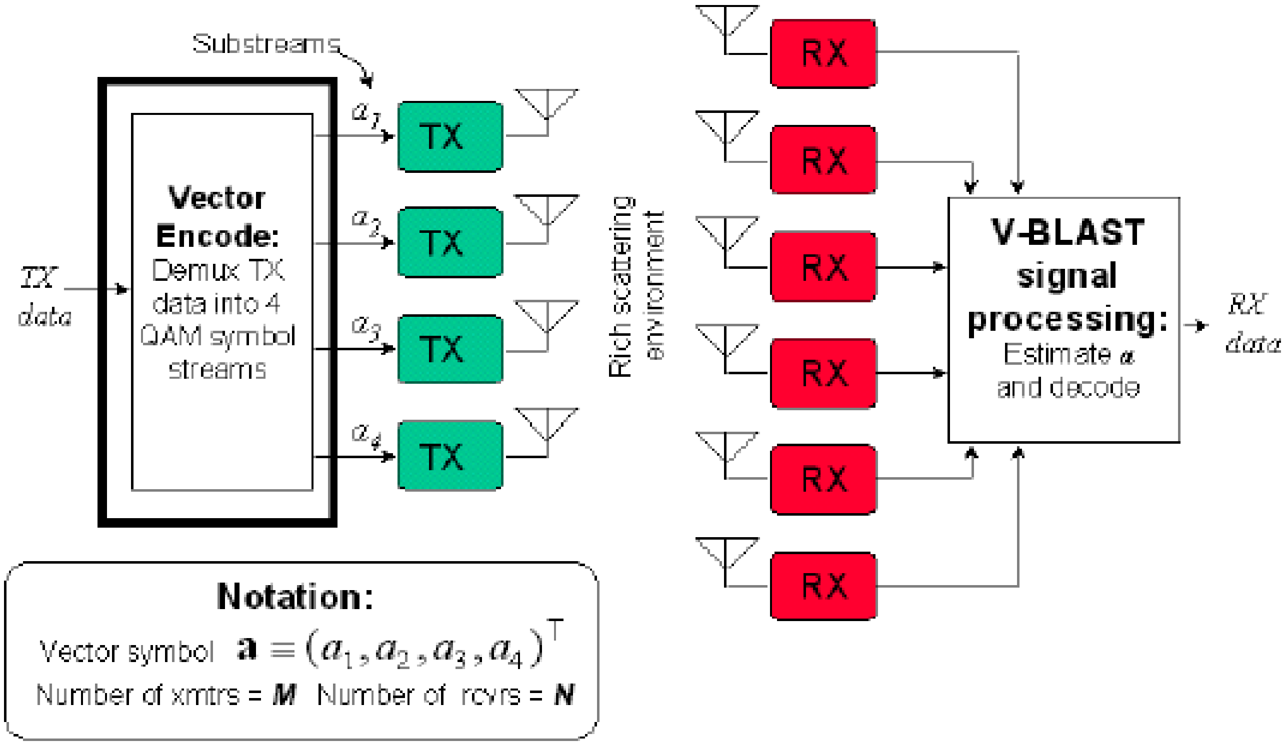
High Throughput Indoor Wireless

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.

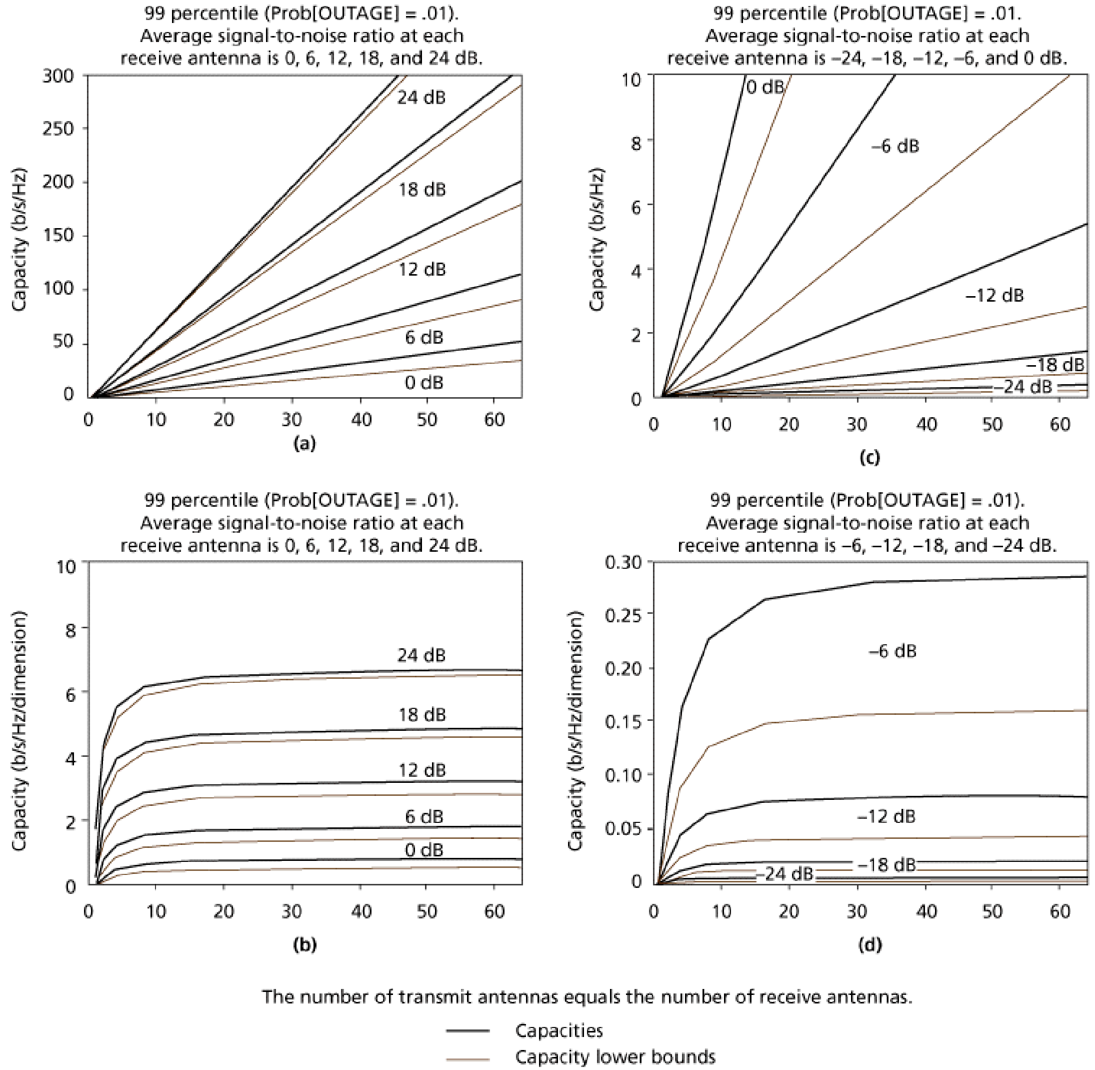
The main drawback of the algorithm is that it requires that your device be big enough to support multiple antennas. (But the Apple I-book already has two antennas built in to support 802.11 wireless networking, so maybe this isn't such a problem.)

BLAST

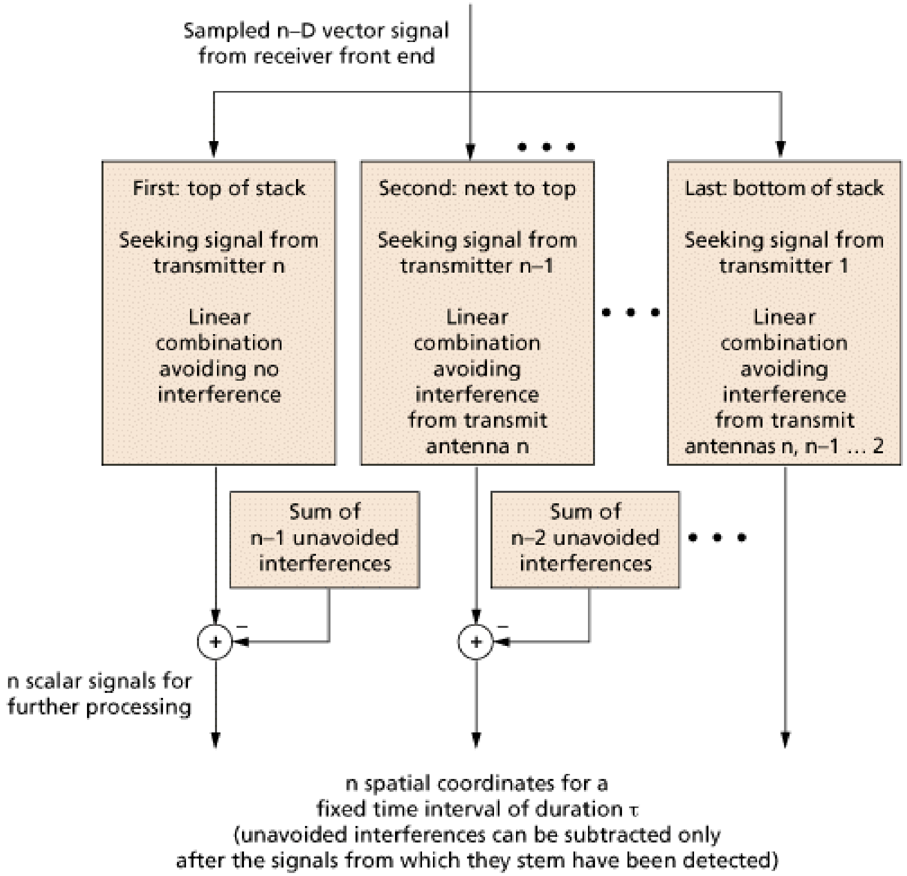


Substreams
TX data
Vector Encode:
Demux TX data into 4 QAM symbol streams
a_1
a_2
a_3
a_4
TX
TX
TX
TX
Rich scattering environment
RX
RX
RX
RX
RX
RX
V-BLAST signal processing:
Estimate a and decode
RX data
Notation:
Vector symbol $\mathbf{a} \equiv (a_1, a_2, a_3, a_4)^T$
Number of xmtrs = ***M*** Number of rcvrs = ***N***

BLAST


99 percentile (Prob[OUTAGE] = .01).
Average signal-to-noise ratio at each
receive antenna is 0, 6, 12, 18, and 24 dB.
Capacity (b/s/Hz)
24 dB
18 dB
12 dB
6 dB
0 dB
(a)
99 percentile (Prob[OUTAGE] = .01.
Average signal-to-noise ratio at each
receive antenna is –24, –18, –12, –6, and 0 dB.
Capacity (b/s/Hz)
0 dB
–6 dB
–12 dB
–18 dB
–24 dB
(c)
99 percentile (Prob[OUTAGE] = .01).
Average signal-to-noise ratio at each
receive antenna is 0, 6, 12, 18, and 24 dB.
Capacity (b/s/Hz/dimension)
24 dB
18 dB
12 dB
6 dB
0 dB
(b)
99 percentile (Prob[OUTAGE] = .01).
Average signal-to-noise ratio at each
receive antenna is –6, –12, –18, and –24 dB.
Capacity (b/s/Hz/dimension)
–6 dB
–12 dB
–18 dB
–24 dB
(d)
The number of transmit antennas equals the number of receive antennas.
Capacities
Capacity lower bounds

BLAST


Sampled n–D vector signal
from receiver front end
First: top of stack
Seeking signal from
transmitter n
Linear
combination
avoiding no
interference
Second: next to top
Seeking signal from
transmitter n–1
Linear
combination
avoiding
interference
from transmit
antenna n
Last: bottom of stack
Seeking signal from
transmitter 1
Linear
combination
avoiding
interference
from transmit
antennas n, n–1 … 2
Sum of
n–1 unavoided
interferences
Sum of
n–2 unavoided
interferences
n scalar signals for
further processing
n spatial coordinates for a
fixed time interval of duration τ
(unavoided interferences can be subtracted only
after the signals from which they stem have been detected)

Conclusions

- The indoor radio channel can 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 get 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).