Surviving in the 2.4GHz Band

Presentation Outline

- Introduction to the 2.4GHz band
- Coexistence problem
- Potential solutions
- Conclusions

Possible Solutions

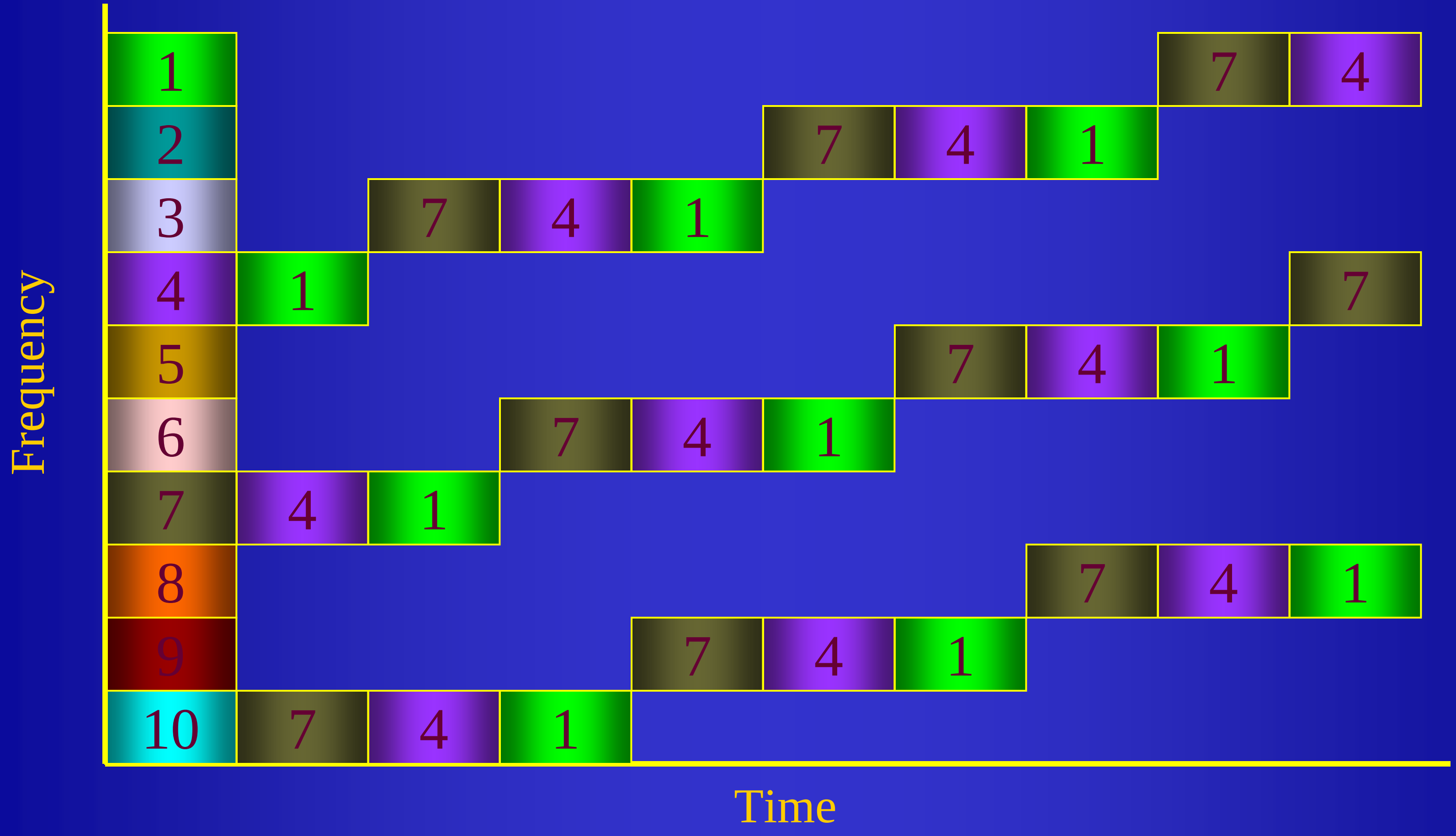
- Regulatory and Standards
  - Spectrum usage regulations
  - Specifications in standards bodies
- Usage and Practices
- Technical Approaches
  - General system approaches
  - Driver layers
  - MAC layers
  - Physical layers
- Alternate Frequency Bands

2.4GHz Scene (USA)

- **Wireless LAN (WLAN):** HomeRF, 802.11, Wi-Fi
- **Wireless PAN (WPAN):** Bluetooth (high/low speed)
- **Other:** residential equipment (microwave oven), cordless phones (DECT), industrial applications (sulphur plasma lighting, RF heating), short range devices (wireless audio/video, RFID systems)

2.4GHz DSSS

2.4GHz FHSS (Bluetooth)



1								7	4
2					7	4	1		
3		7	4	1					
4	1								7
5						7	4	1	
6			7	4	1				
7	4	1							
8							7	4	1
9				7	4	1			
10	7	4	1						

Definitions

- **Coexistence:** multiple wireless devices are said to *coexist* if they can be collocated without significantly impacting the performance of any of these devices
- **Interoperability:** the ability for two devices to perform a given task using a common, single set of rules

Definitions (cont.)

- **Collaborative Coexistence Mechanism:** it is possible for the WLAN and WPAN to exchange information between one another
- **Non-collaborative Coexistence Mechanism:** there is no method to exchange information between WLAN and WPAN networks

Definitions (cont.)

- **In-band Interference:** undesired energy in frequencies that a radio uses to transmit a given signal
- **Out-band Interference:** undesired energy in frequencies that a radio does not use
- **White Interference:** wideband noise with no deterministic behavior over time or frequency
- **Colored Interference:** narrowband noise with a specific behavior in time and frequency

Coexistence Parameters

- Interference between a Bluetooth piconet and a 802.11 node depends on several factors:
  - Distance of STA, AP from Bluetooth piconet
  - Local propagation conditions (multipath)
  - 802.11 data rate, TX power
  - Bluetooth piconet utilization

Collision Types

- Simultaneous TX is usually ok
- Simultaneous RX is always ok
- Problem arises when one device is TX and the other is RX
  - Co-channel results are catastrophic
  - Outside channel impact depends on channel filter

Performance Effects

- **Voice connections:** sensitive to loss of packets; potentially asymmetric susceptibility for extended range due to location
- **Audio:** very sensitive to errors and very asymmetric susceptibility to interference
- **Video:** sensitive to uniformly distributed errors more than to burst of errors; symmetric susceptibility if bi-directional
- **Data connections:** tolerant to interference within certain delay bounds; asymmetric due to location

Practical Interference Results

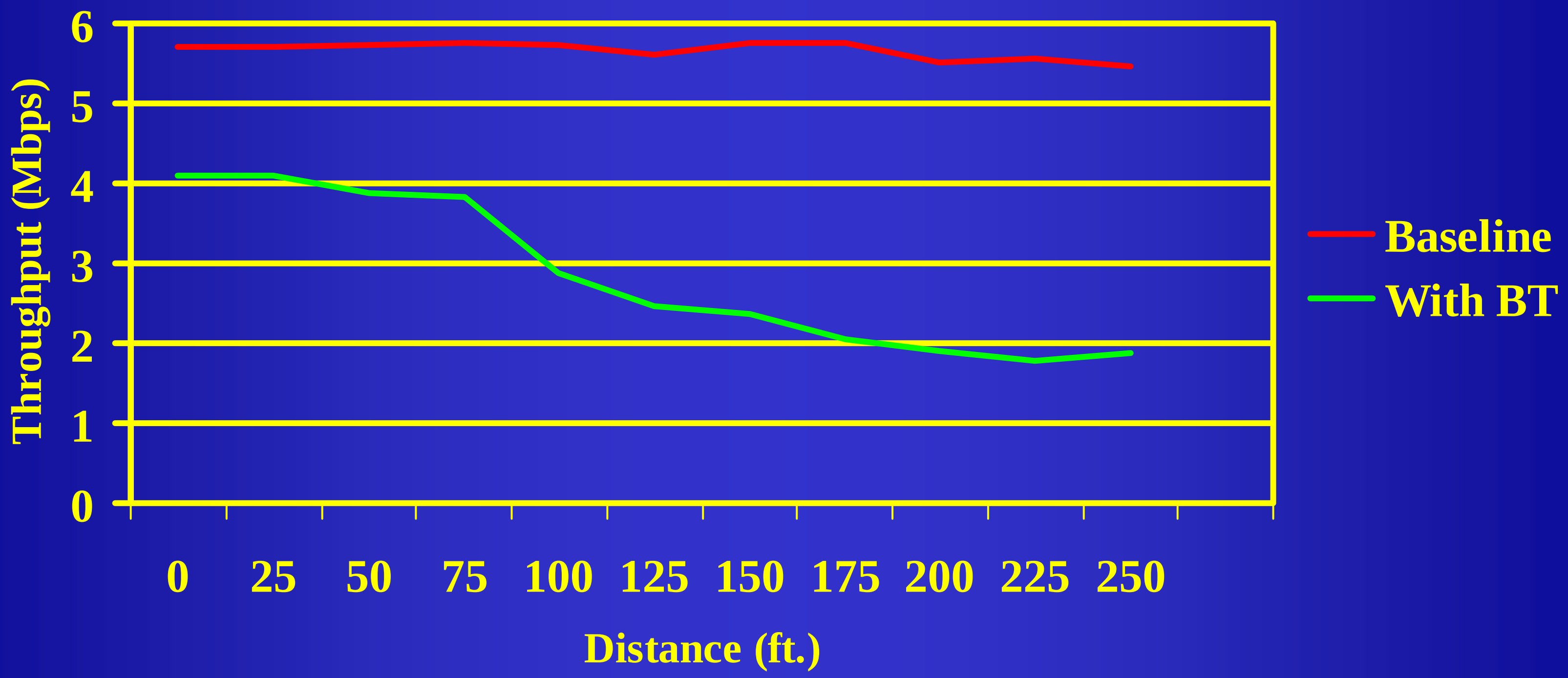
- Evaluate three different network topologies:
  - ***SCENARIO A:*** 802.11 throughput versus distance when a Bluetooth piconet is located next to an 802.11 access point
  - ***SCENARIO B:*** 802.11 throughput versus distance when a Bluetooth piconet is located next to an 802.11 station
  - ***SCENARIO C:*** Bluetooth throughput versus distance when an 802.11 BSS is located next to a Bluetooth slave

Scenario A

Scenario Assumptions:

AmbiCom Wave2Net AP and STA 802.11 products; the Packet Fragmentation Threshold is set to 2312b, and the TxPower is set to 30mW

AmbiCom Air2Net BT product; the TxPower is set to 100mW

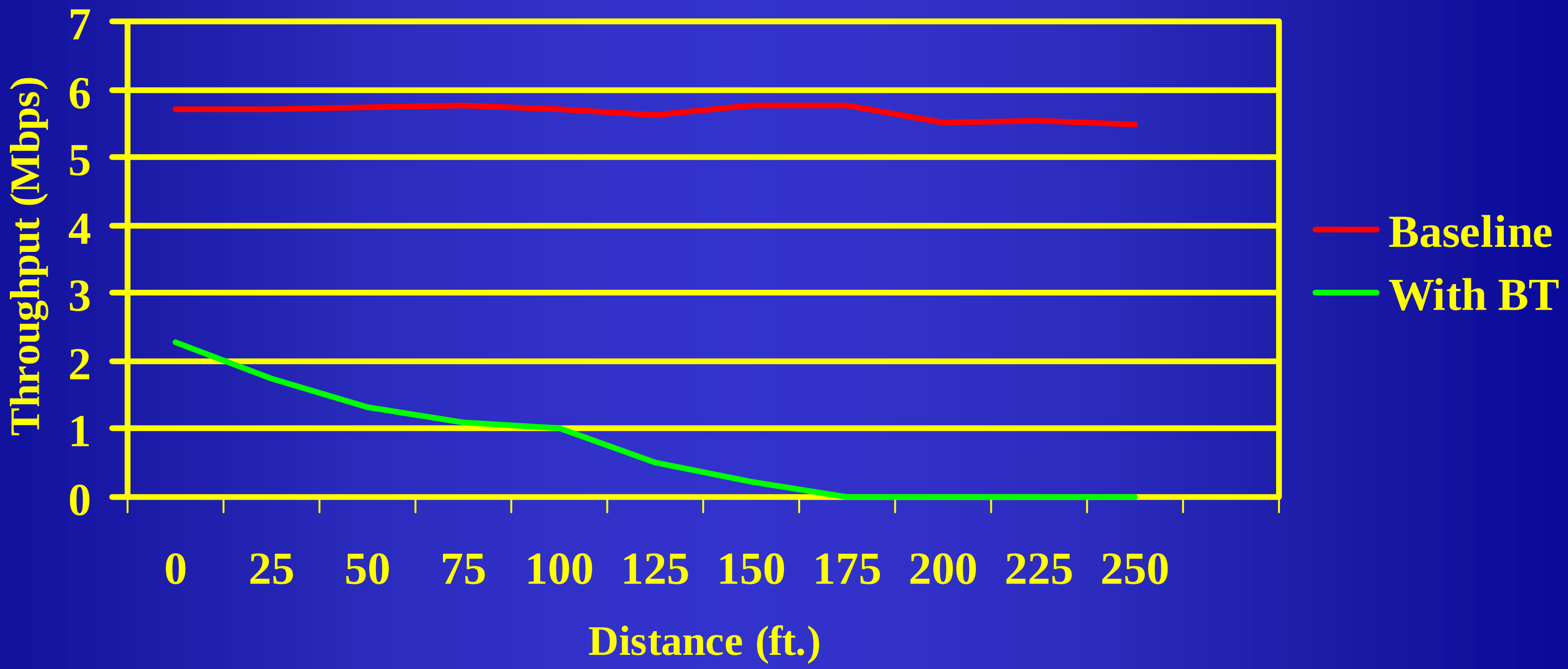


Scenario B

Scenario Assumptions:

AmbiCom Wave2Net AP and STA 802.11 products; the Packet Fragmentation Threshold is set to 2312b, and the TxPower is set to 30mW

AmbiCom Air2Net BT product; the TxPower is set to 100mW

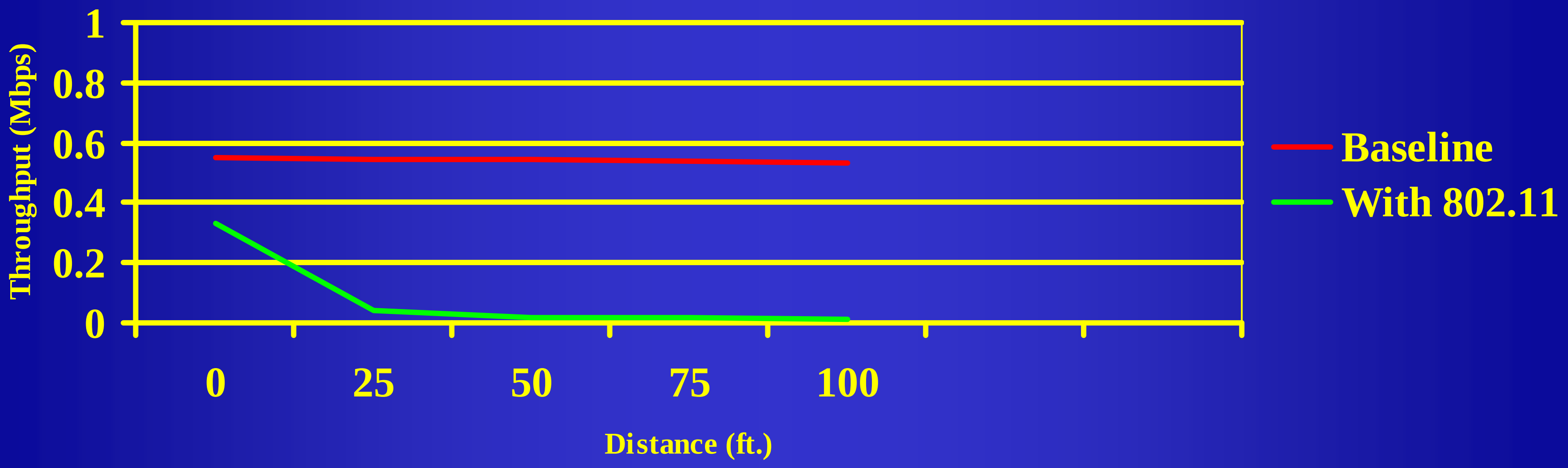


Scenario C

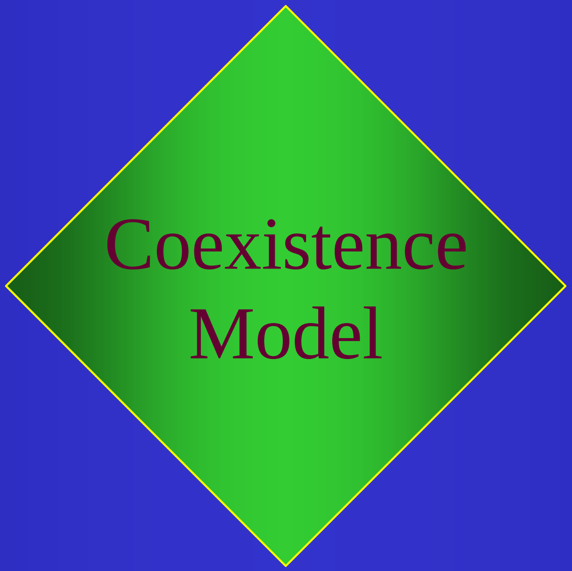
Scenario Assumptions:

AmbiCom Wave2Net AP and STA 802.11 products; the Packet Fragmentation Threshold is set to 2312b, and the TxPower is set to 30mW

AmbiCom Air2Net BT product; the TxPower is set to 100mW



Coexistence Model



PHY Layer Models

MAC Layer Models

Coexistence Model

Data Traffic Models

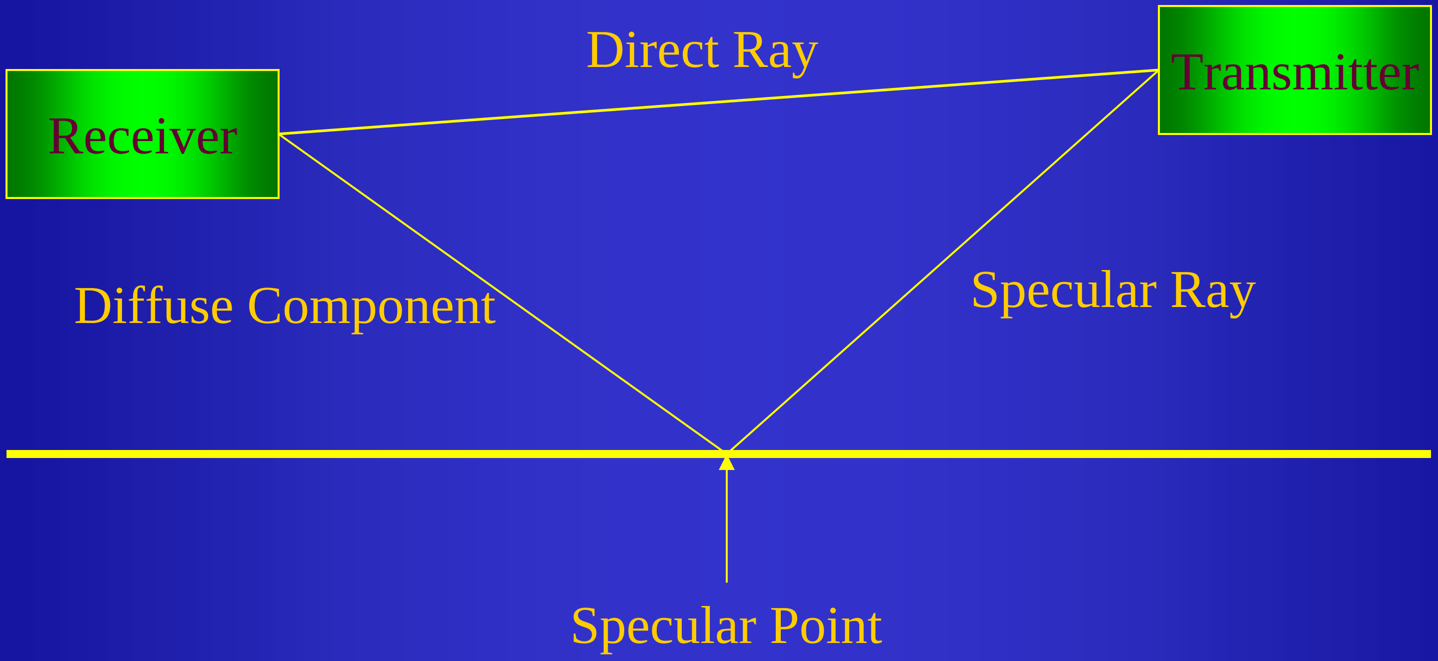
RF Propagation Models

RF Propagation Models

Propagation Phenomena

- Propagation impairments:
  - Reflection, diffraction
  - Transmission loss through objects
  - Channeling of energy in corridors
  - Motion of persons/objects in the room
- Impact:
  - Path loss
  - Temporal/Spatial variation of path loss
  - Multipath effects (diffuse, specular)
  - Polarization mismatch

Mutlipath Effects



Direct Ray

Receiver

Transmitter

Diffuse Component

Specular Ray

Specular Point

Path Loss

- Path Loss generic formula:
  - N – distance power loss coefficient
  - f – frequency
  - d – distance between nodes
  - L_f – floor penetration loss factor
  - n – number of floors penetrated

$$L_{total} = 20\log(f) + N\log(d) + L_f(n) - 28$$

Path Loss (cont.)

- Path Loss typical values:
  - N = 20 for free space, 28 for residential, 30 for office, 22 for commercial
  - L_f = 4n for residential, 15+4(n-1) for office, 6+3(n-1) for commercial

Path Loss (cont.)

- The formula presented for path loss represents the average of mean path loss
- Actual value of path loss varies dependent on ***shadow fading*** (lognormal with variance 8 for residential, 10 for office, 10 for commercial) and ***multipath fading*** (Raleigh, Rician, Nakagami-m)

Path Loss (cont.)

- The bit rate for Bluetooth is 10Mbps; that means that a bit duration is 100ms or 30m long
- Frequency selective fading responsible for ISI occurs when the path differences are significant portions of 30m
- Maximum propagation delay for small buildings is 100ns or 30m long; that is a 30dB drop in power relative to a signal that is received 1m away from the TX
- As a result, Bluetooth path loss in residential homes is flat fading, where all multipaths arrive within the information symbol

Multipath Delay Spread

- Multiple paths result in a time delay spread in the channel
- Rough estimate can be obtained from the dimensions of the room and the fact that RF waves travel 1m every 3.3ns
- Delayed signals form a time-varying linear filter
- Typical values of RMS delay spread is 70ns for residential, 100ns for office, 150ns for commercial

Multipath Delay Spread (cont.)

- Statistical modeling through the Wide-Sense Stationary Uncorrelated Scattering (WSSUS) approach
- Replace real scattering paths with only a few uncorrelated multipath components
- Combine unresolved multipath components of similar path length

Antenna Polarization

- Circularly polarized antennas can reduce RMS delay spread
- Directional antennas can reduce RMS delay spread

Moving Objects

- Movement causes temporal variation in the indoor propagation characteristics (time-varying channel)
- A person into the path of a LOS signal can cause 5 to 10dB drop in received power level in the 2.4GHz band
- For WPANs, Doppler spreads are negligible over long periods of time (i.e. never reach the maximum frequency of 9.6Hz recommended by PCS in the 2.4GHz band)

Other

- Effect of Location of XMTR and RCVR
- Effect of Human Occupancy, Home Design, Building Material

Simplified Indoor Propagation Model

- Simplified indoor propagation model: For the first 8m assume line-of-sight; beyond 8m assume that path loss increases as a function of **r^n**, where **r** is the range and **n = 3.3**

$$
\begin{aligned}
L_{path} &= 20 \log\left(4\pi r / \lambda\right), r \le 8m \\
&= 58.3 + 33 \log\left(r / 8\right), r > 8m
\end{aligned}
$$

PHY Layer Models

Model I

- What is the probability that from a given pair of consecutive Bluetooth slots, at least one of the channels overlaps with a given wideband 802.11 channel?
- Since there is 1/3 probability that any given narrowband channel overlaps with a given wideband channel, Prob. = 1 – (2/3)^2 = 56% packet error rate

Model I (cont.)

- Let **H** be the duration of a Bluetooth hop and **L** be the duration of an 802.11 packet
- Minimum number of hops which overlap is $\lceil L/H \rceil$, and the maximum is $\lceil L/H \rceil + 1$

Model I (cont.)

- The probability that an 802.11 packet of duration L experiences no Bluetooth collisions is:

$$(2/3)^{\lceil L/H \rceil}\left(\lceil L/H \rceil - L/H\right) + (2/3)^{\left(\lceil L/H \rceil + 1\right)}\left(1 - \lceil L/H \rceil + L/H\right)$$

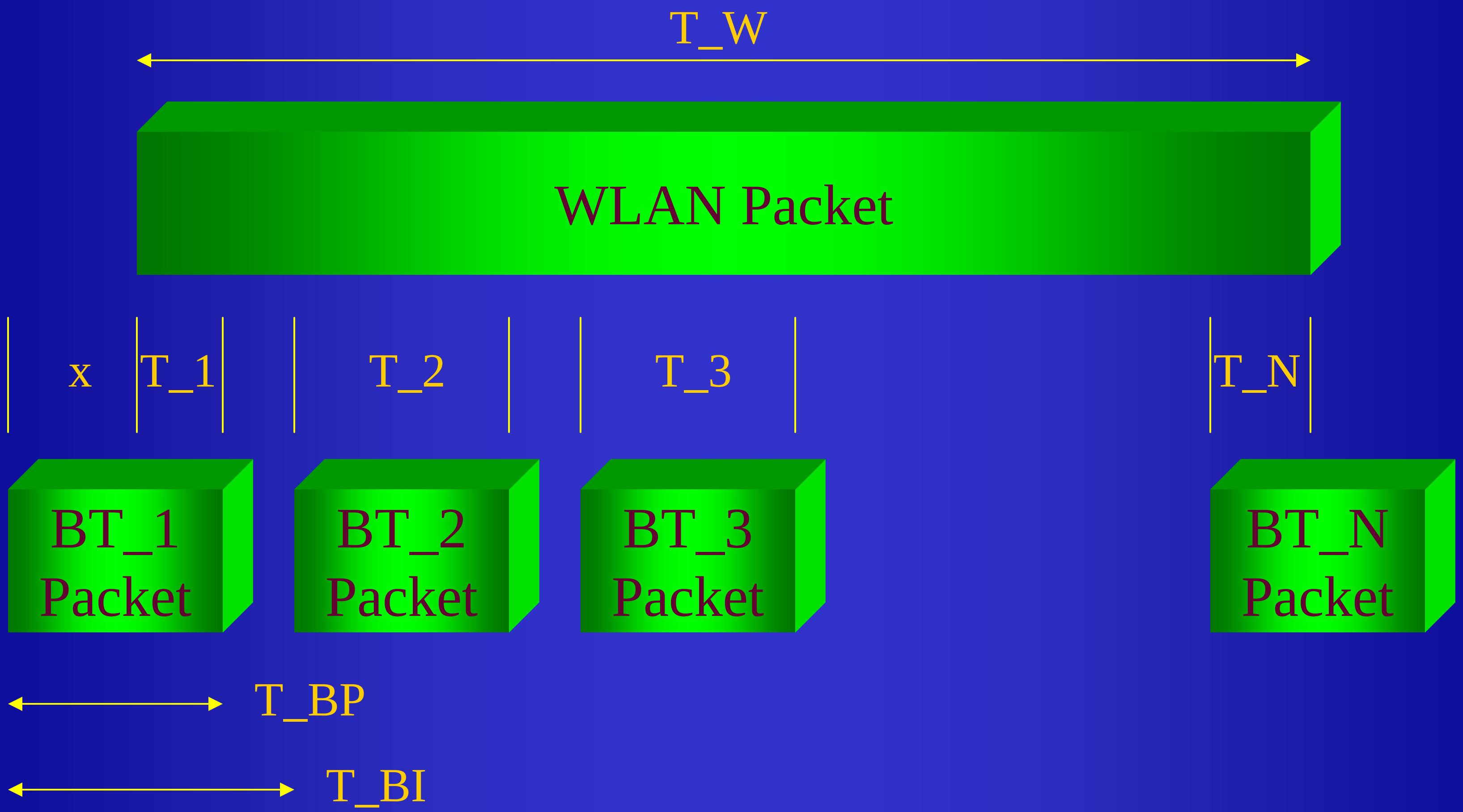
Model I (cont.)

- Let **d** be the difference between the last Bluetooth hop and the start of an 802.11 packet
- An 802.11 packet will overlap:
  - $\lceil L/H \rceil$ Bluetooth dwell periods when $0 < d <= \lceil L/H \rceil * H - L$
  - $\lceil L/H \rceil + 1$ Bluetooth dwell periods when $\lceil L/H \rceil * H - L < d <= H$

Model II

- An 11Mbps DSSS radio can provide reliable service with a narrow band interferer such as Bluetooth transmitter falling within its pass band as long as the Signal-to-Interference Ratio (SIR) is greater than roughly 10dB
- To determine the probability a collision will occur, the effective bandwidth of the DS system must be estimated: for a CCK waveform is about 20MHz
- Prob. = 20/79 ~ 1/4

Model III



T_W

WLAN Packet

x

T_1

T_2

T_3

T_N

BT_1 Packet

BT_2 Packet

BT_3 Packet

BT_N Packet

T_BP

T_BI

Model III (cont.)

$$p_x(k) = 1/K, k = 1,2,\ldots, K$$

$$P(GP) = \sum_{k=1}^{K} P(GP \mid x = k) p_x(k)$$

$$P(GP \mid x = k) = P(GS_1, GS_2, \ldots, GS_N \mid x = k)$$

$$P(GP \mid x = k) = \prod_{i=1}^{N} P(GS_i \mid x)$$

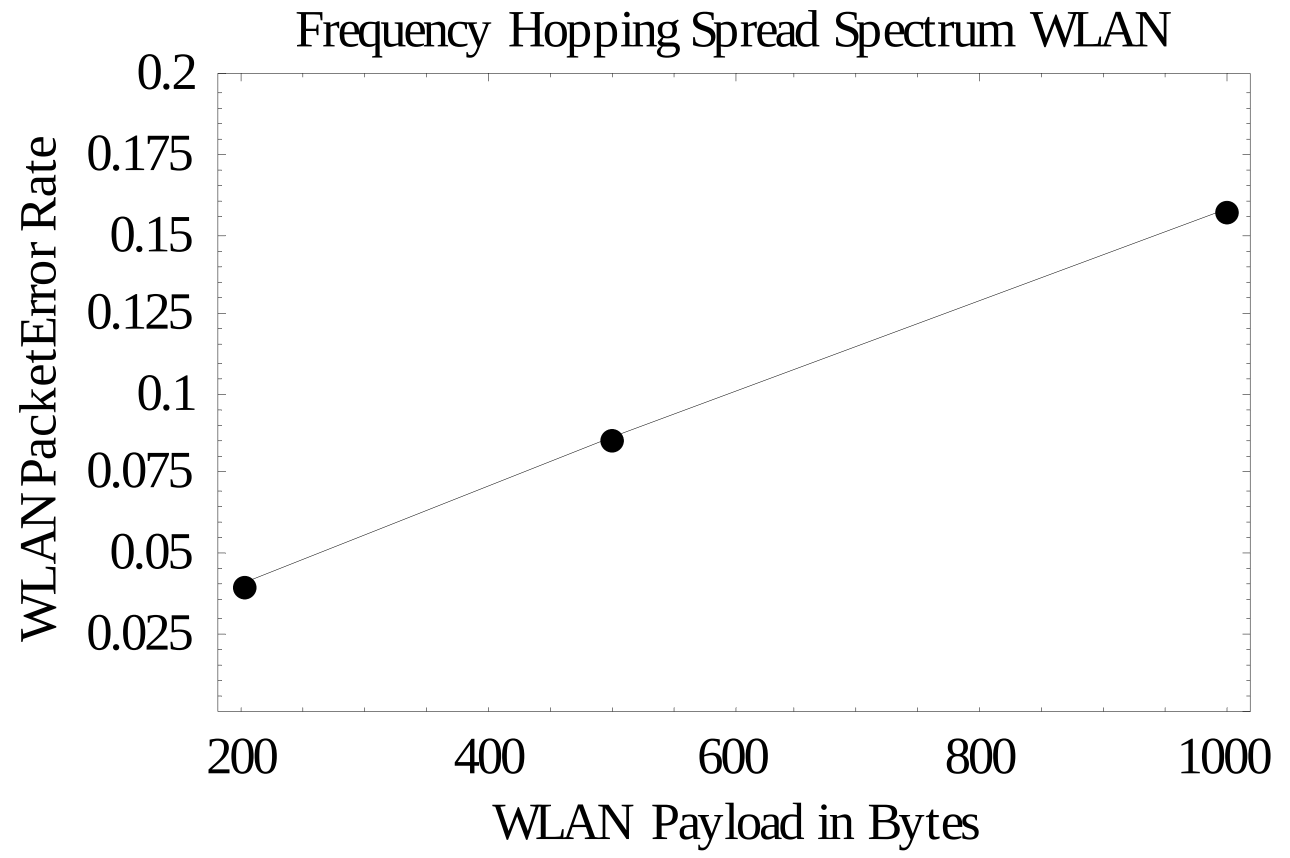
$$p_{f_i}(j) = 1/79, j = 1,2,\ldots, 79$$

$$P(GS_i \mid x = k) = 1/79 \sum_{j=1}^{79} P(GS_i \mid x = k, f_i = j)$$

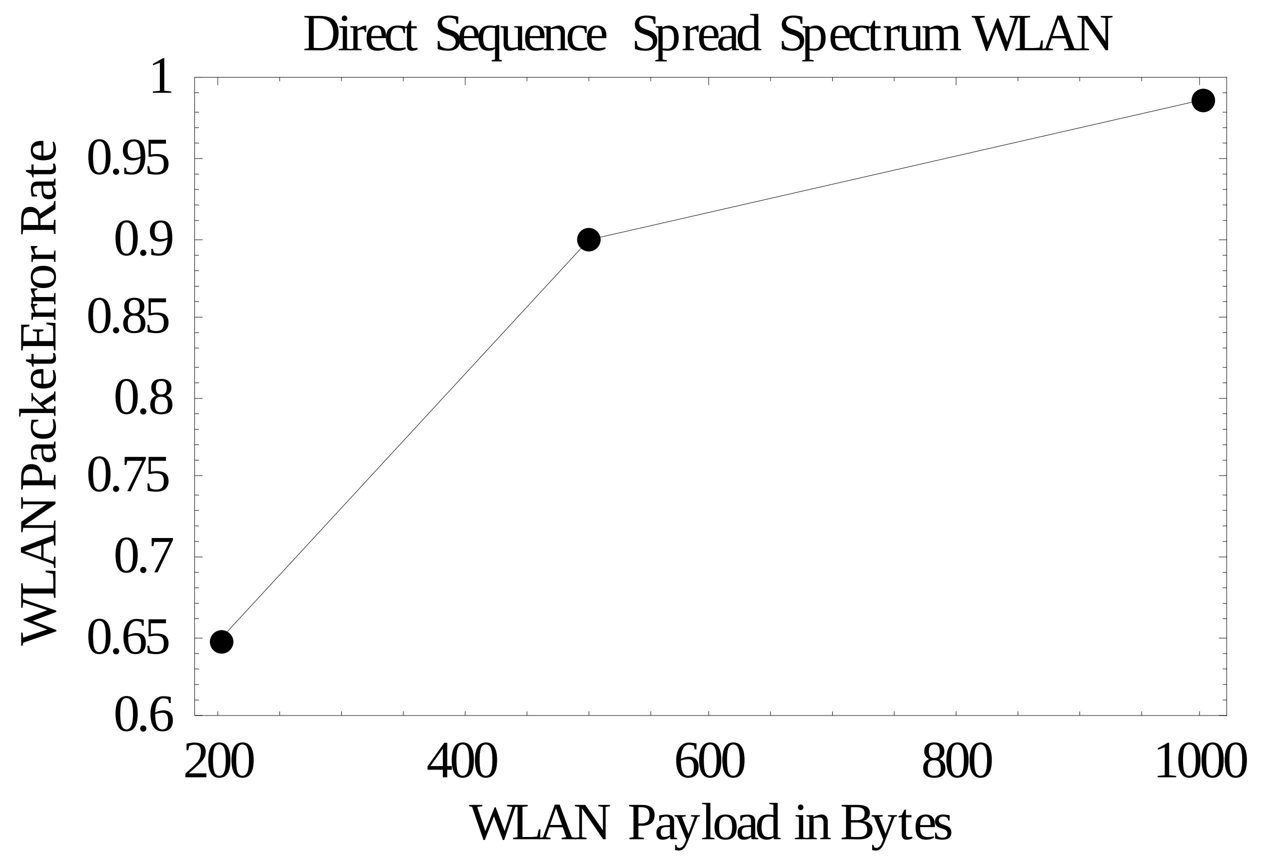
$$p_{e|\rho_i, j} = P(e \mid \rho_i, f_i = j) = g(\rho_i, j)$$

$$P(GS_i \mid x = k, f_i = j) = (1 - p_{e|\rho, j})^{m_i}$$

1 Mbps FHSS WLAN Results

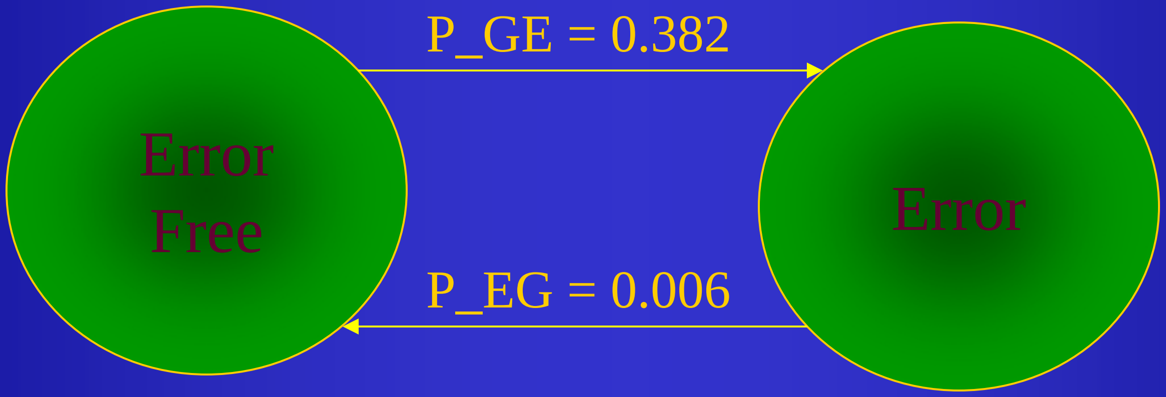


1 Mbps DSSS WLAN Results

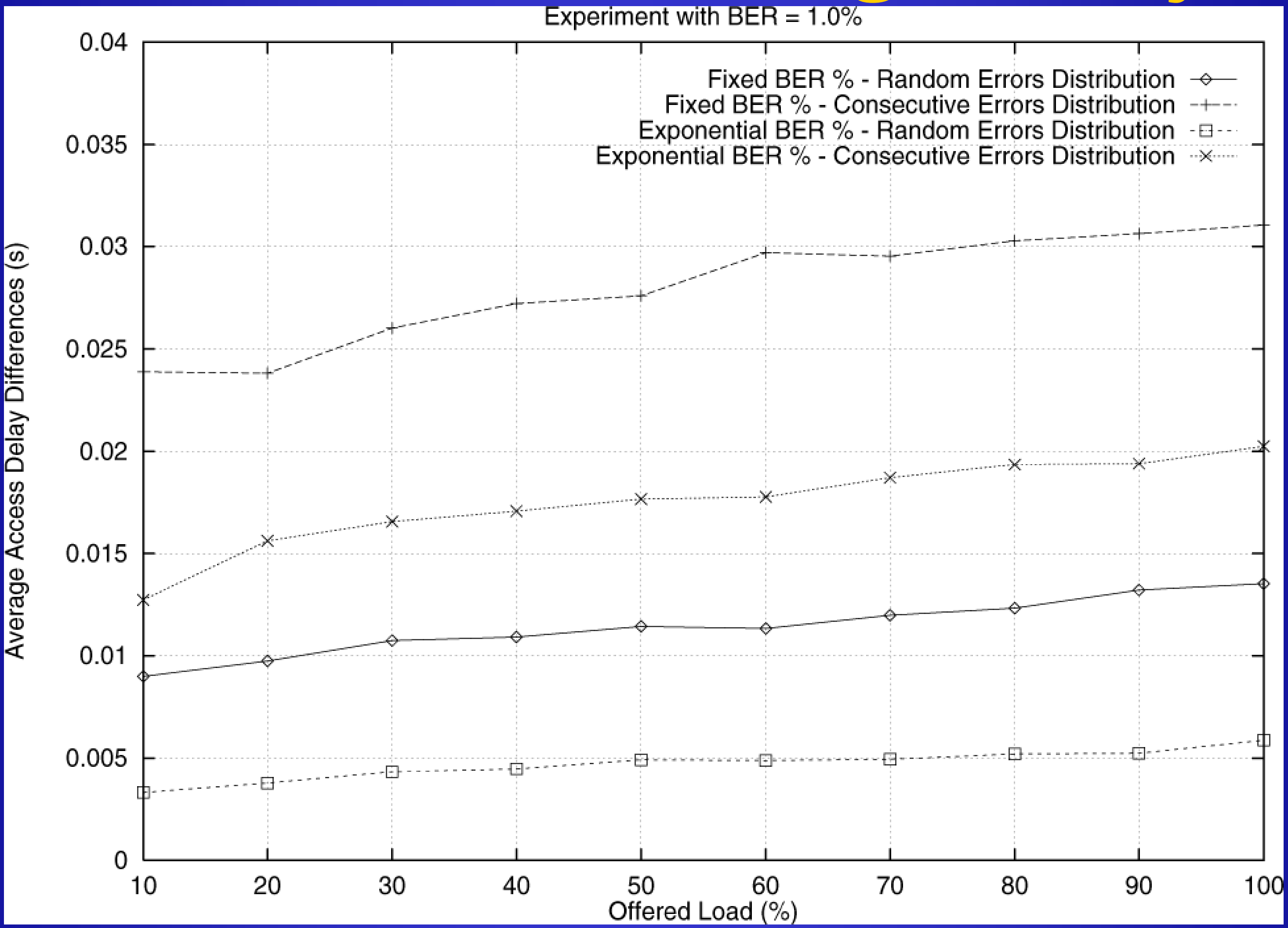


Model IV

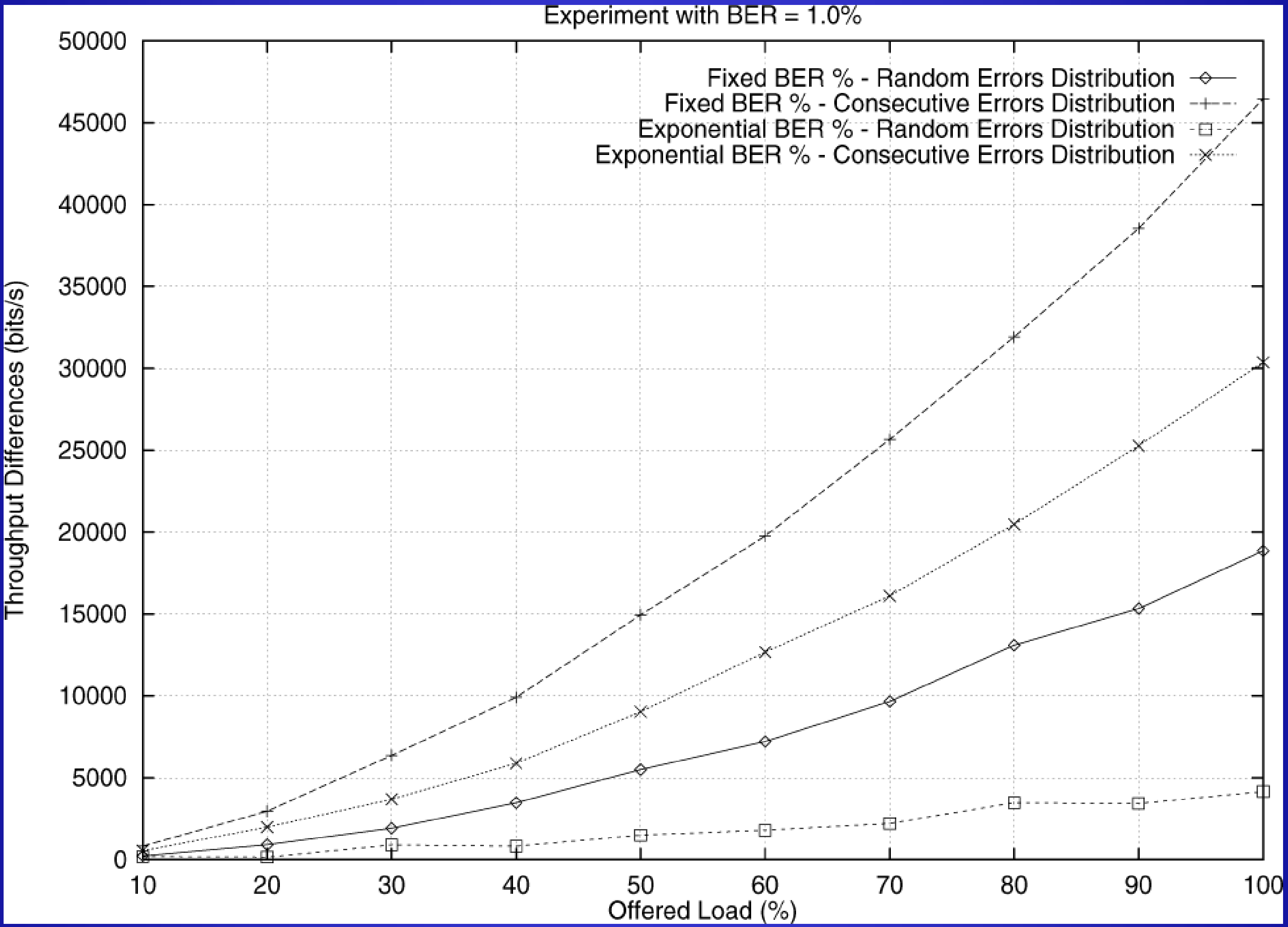
- Trace the behavior of existing implementations and apply the lessons learned to evaluate new designs
- BER based on a two-state Markov model derived from a multiple-state Fritchman model



BER = 1%, Average Delay



BER = 1% , Throughput



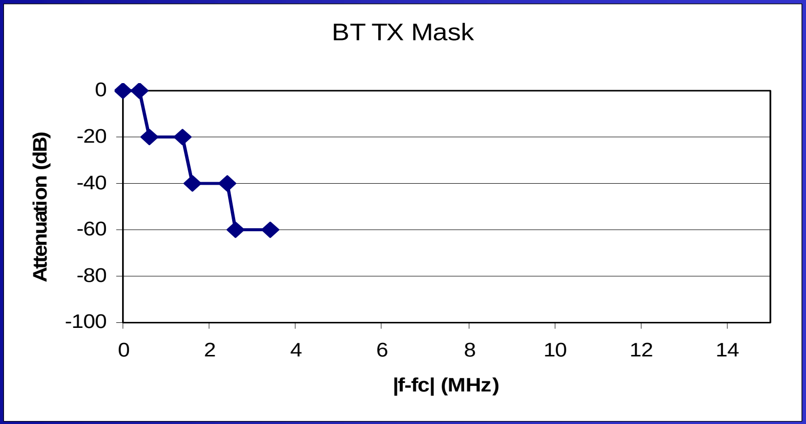
Model V

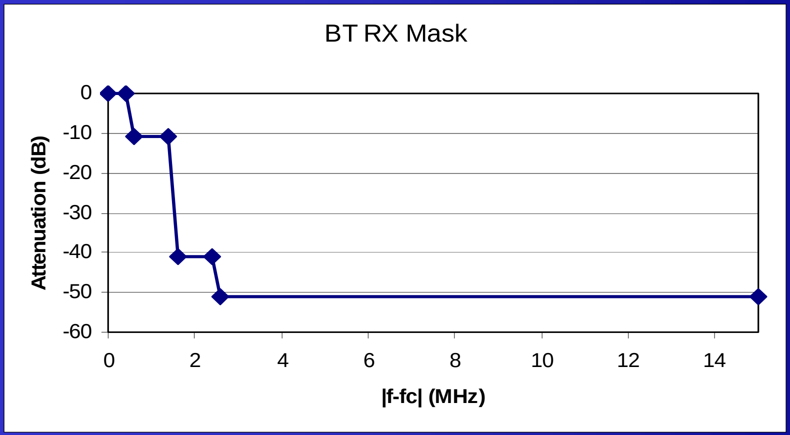
- **BT:** BER = 0.5e^(-SNIR/2)
- **802.11 DS 1Mbps:** BER = Q(sqrt(11*2*SNIR/2))
- **802.11 DS 2Mbps:** BER = Q(sqrt(5.5*2*SNIR/2))
- **802.11 DS 5.5/11Mbps:** BER = Q(sqrt(2*SNIR*R_c*W_m)), where R_c is the code rate and W_m is the codeword distance

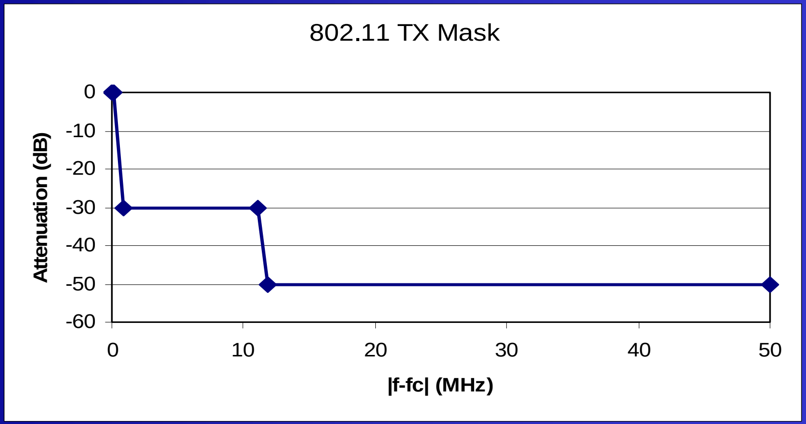
Modeling Issues

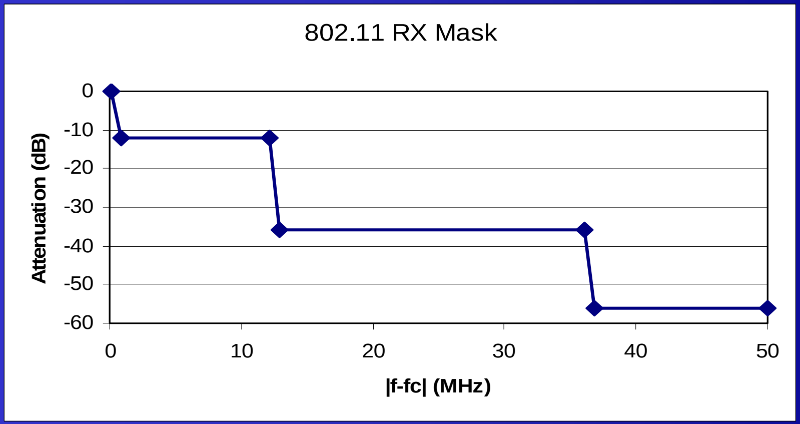
- Sensitivity
- Receiver architecture effects
  - Co-channel interference
  - Adjacent and alternate channel
  - Image frequency
  - Desensitization
- Capture ratio (limiter effects)
- Compression of LNAs at close proximity

Transmit and Receive Masks


BT TX Mask


BT RX Mask


802.11 TX Mask

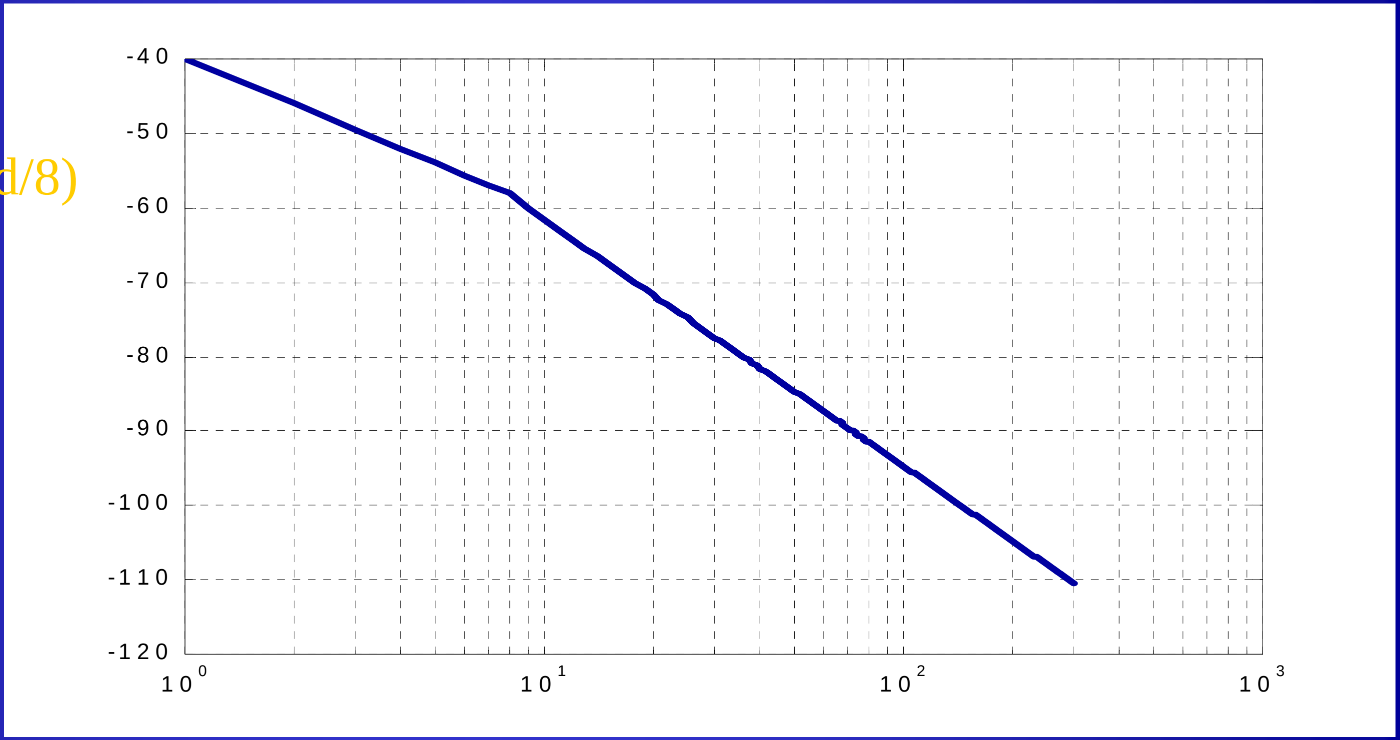

802.11 RX Mask

Path loss model

- For d<8m,

  40.2+20log d
- For d>8m,

  58.5 + 33log(d/8)



BER computation based on SNIR

- BT

  Treat as non-coherent FSK

  BER = 0.5 $e^{-SNIR/2}$

- 802.11b DS 1 Mb/s

  BER = Q(sqrt(11*2*SNIR/2))

- 802.11b DS 2 Mb/s

  BER = Q(sqrt(5.5*2*SNIR/2))

- 802.11b DS 5.5 and 11 Mb/s

  Treat as block code

  BER = Σ Q(sqrt(2*SNIR*Rc*Wm))

  Rc = code rate

  Wm = codeword distance

BER computation (cont.)

- 802.11b DS 5.5 Mb/s

  Codeword error probability: PEW

  PEW = 14 Q(sqrt(8 SNIR)) +
  Q(sqrt(16 SNIR));

  Each codeword encodes 4 bits, therefore

  BER = $1-(1-\text{PEW})^{1/4}$

- 802.11b DS 11 Mb/s

  Codeword error probability: PEW

  PEW = 24 Q(sqrt(4 SNIR)) +
  16 Q(sqrt(6 SNIR)) +
  174 Q(sqrt(8 SNIR)) +
  16 Q(sqrt(10 SNIR)) +
  24 Q(sqrt(12 SNIR)) +
  Q(sqrt(16 SNIR));

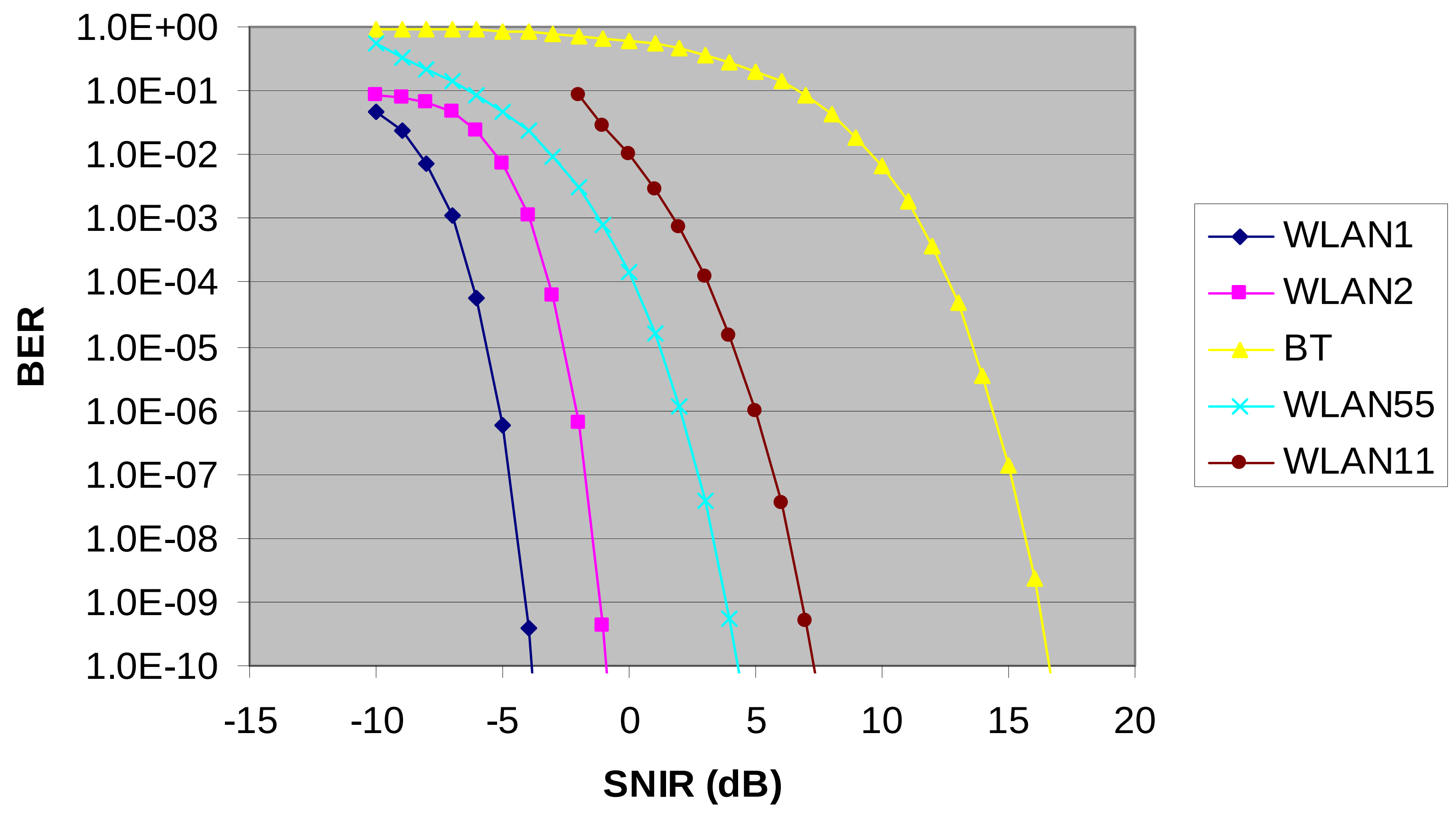
  Each codeword encodes 8 bits, therefore

  BER = $1-(1-\text{PEW})^{1/8}$

BER computation (cont.)

- BER curves used within certain limits: (for code efficiency)
  - WLAN: -3dB < SNIR < 10dB
  - BT: 1dB < SNIR < 20 dB

BER vs. SNIR graph



Imperfections

- Even though a transmitter operates in a given bandwidth space, sideband signals are always present and cause interference to other systems sharing the same frequency band
- Receiver filters are not perfect; no filter can provide a single cut-off number such that every signal just inside or outside the passband is always filtered out appropriately

The Adaptive Solution

- ***Adaptive Frequency Hopping (AFH)***
- ***Adaptive Power Control (APC)***
- ***Adaptive Filtering (AF)***
- ***Adaptive Modulation (AM)***
- ***Adaptive Error Coding (AEC)***
- ***Adaptive Antenna Arrays (AAA)***

AFH

- While conventional frequency hopping is blindly passive, AFH classifies channels and adaptively selects from the pool of preferred channels
- AFH can be implemented as a Bluetooth profile
- Link assessment criteria:
  - Error checking of CAC, HEC, CRC plus packet truncation
  - PER, BER test by LMP
  - RSSI

AFH (cont.)

- AFH by Zander:
  - Based on a feedback channel similar to the one used in ***Automatic Link Establishment*** (**ALE**)
  - The entire frequency map is transmitted at every updating instant

AFH (cont.)

- AFH by Knuth et al.:
  - – Periodic scanning of the channel during idle time
  - – A score is applied to each channel
  - – Selection of the preferred channel is based on score

AFH (cont.)

- AFH by Gillis et al.:
  - Determine the link quality (measuring the interference level) of each channel of a First Group of predetermined channels
  - Select one or more channels from a Second Group of predetermined channels to substitute channels from the First Group with high interference

AFH (cont.)

- AFH by Lawrey et al.:
  - Assume a multiuser OFDM system
  - Each user is allocated carriers which have the best SNR for that user
  - Most users can be allocated the best carriers for them with minimal clashes
  - Virtually eliminates frequency selective fading

AFH (cont.)

- AFH by Treister et al.:
  - The master broadcasts a new packet type to all slaves to inform them of a new hopping sequence
  - The master appends some bytes to the payload to indicate the channel number for the slave to transmit in the next time slot

AFH (cont.)

- AFH by Chen et al.:
  - Select a set of partition sequences from three possible sets (partition 1,2,3 for Bluetooth) so that the original sequence is mapped into a new sequence that does not overlap with a DS channel (channel 1,6,11 for 802.11)
  - From the time slots slots reserved by the traffic requirements, calculate the partition usage vector for partition sequences; calculate the average hit probability H(p) of all partitions, and select the partition sequences with minimal H(p)

AFH (cont.)

802.11 Channel	802.11 Range	Bluetooth Partition	Bluetooth Channel
1	2400-2424	1	0-22, 75-77
6	2425-2449	2	23-47, 78
11	2450-2474	3	48-72, 73-74

AFH (cont.)

- AFH by Batra et. al.:
  - Group good and bad channels according to the Bluetooth packet length that needs to be serviced (i.e. use a group of 2 channels for DM1, 4 channels for DM3, 6 channels for DM5)
  - The master must compile a list of good and bad channels/windows, and transmit this information to the slaves in the piconet

APC

- One way to improve coexistence is to limit the amount of unnecessary signal energy being received
- By using APC the transmitter can update the power level based on the receiver Carrier to Interference Ratio (CIR), or RSSI
- For Bluetooth devices, adaptive power control can be implemented as part of a Bluetooth profile based on the different power levels supported in the standard

APC (cont.)

- 802.11 devices currently implement a rate shifting control algorithm where SNR, SIR, PER, etc. are used to select the maximum rate for a given PER
- A joint rate shift and power control approach can be implemented by just adding operational points at lower power levels to the shifting algorithm
- **Note:** IEEE 802.11 specifies DS PLME MIB *PowerLevel* attributes but are not supported!!

AF

- Bluetooth behaves like a single random tone jammer (narrowband interference) for high data rate 802.11 devices
- Wideband filtering causes minor reduction of the interference
- Use AF (i.e. bandpass cavity, notch filter) to sharpen selectivity and avoid a potential receiver desensitization

AM

- For a predicted SNIR of each channel, the modulation level is maximized under the constraint of a certain probability of symbol rate
- To find the threshold where the modulation format has to change assume a given symbol error probability and calculate the different modulation formats
- AM where the data rate changes according to the perceived link conditions is already part of 802.11 devices

AM (cont.)

- OFDM is more immune to single tone jammers like Bluetooth
- 8PSK has better error performance over OFDM for AWGN channel

AEC

- Fixed error control policies introduce too much overhead in clear environments, or are not aggressive enough for congested environments
- Adaptive FEC algorithms try to control the degree of redundancy based on the dynamic characteristics of the wireless environment
- AEC can be further enhanced based on the particular characteristics of the current application; i.e. different patterns of errors might be tolerable for different applications

AAA

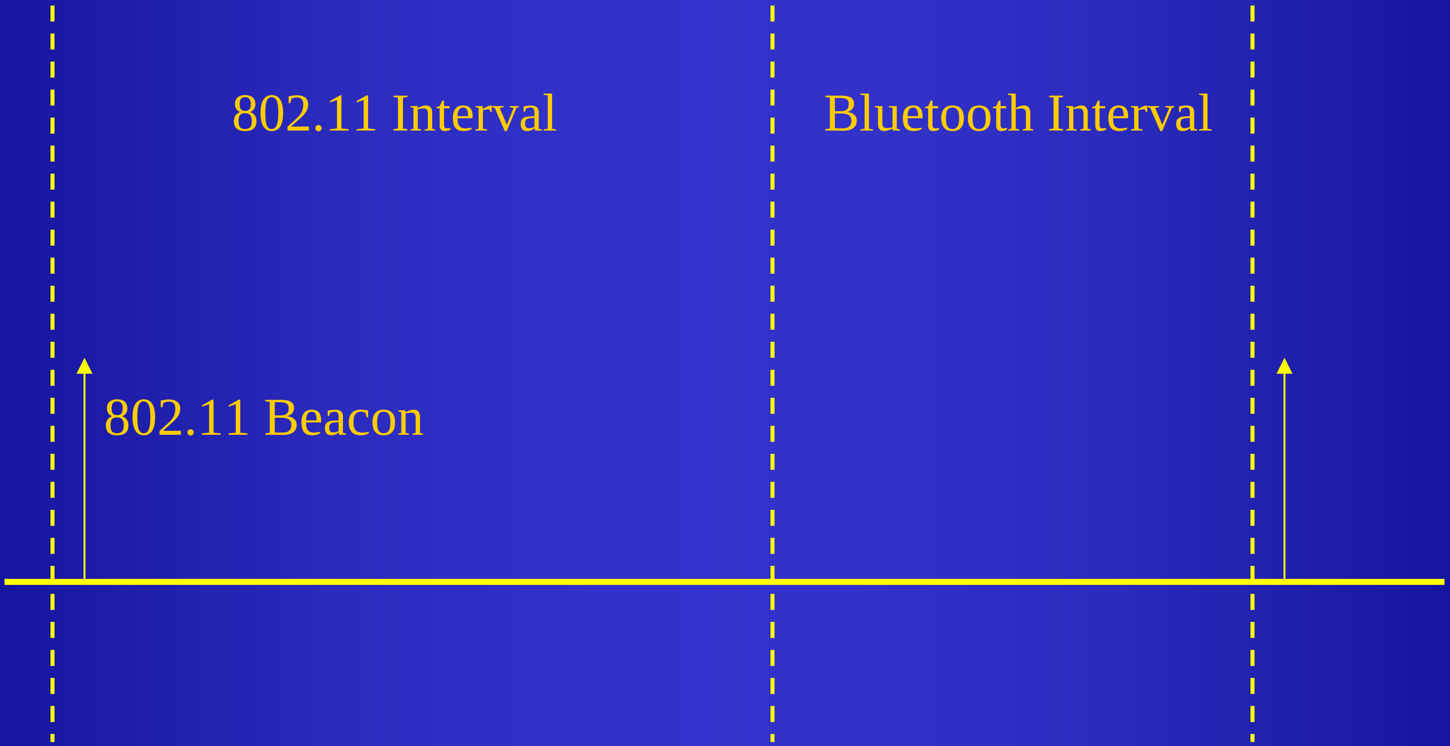
- An antenna array consists of a number of identical antenna elements arranged in a particular geometry
- High speed DSP algorithms can be used at the base station as adaptive spatial filters that can provide a dynamic, optimal antenna radiation pattern as conditions in the network change
- Improves signal quality and capacity of the wireless network

MAC Layer Models

Model I

- For Bluetooth and 802.11 devices that are within a 10cm range use a collaborative coexistence mechanism
- TDMA results in total orthogonality if Bluetooth and 802.11 time intervals do not overlap
- Subdivide the 802.11 beacon-to-beacon interval into two programmable subintervals: one for Bluetooth and one for 802.11

Model I (cont.)



802.11 Interval

Bluetooth Interval

802.11 Beacon

Model I (cont.)

- Throughput of 802.11 and Bluetooth can be regulated through a ***coordinator unit*** that uses statistical contention to resolve conflicts
- Only the master of the Bluetooth piconet needs to be modified
- It is possible to multiplex the antenna in a common portable system between Bluetooth and 802.11
- Supports only ACL links

Model II

- ***Adaptive packet fragmentation*** can be used by the 802.11 AP so that the optimal packet length is chosen for the BSS, according to the perceived link quality (SNR, SIR) from the physical layer
- ***Adaptive packet selection*** (Bluetooth):
  - Continuous good channels: use multi-slot packets; can omit FEC
  - Noisy channels: use single slot packets with FEC

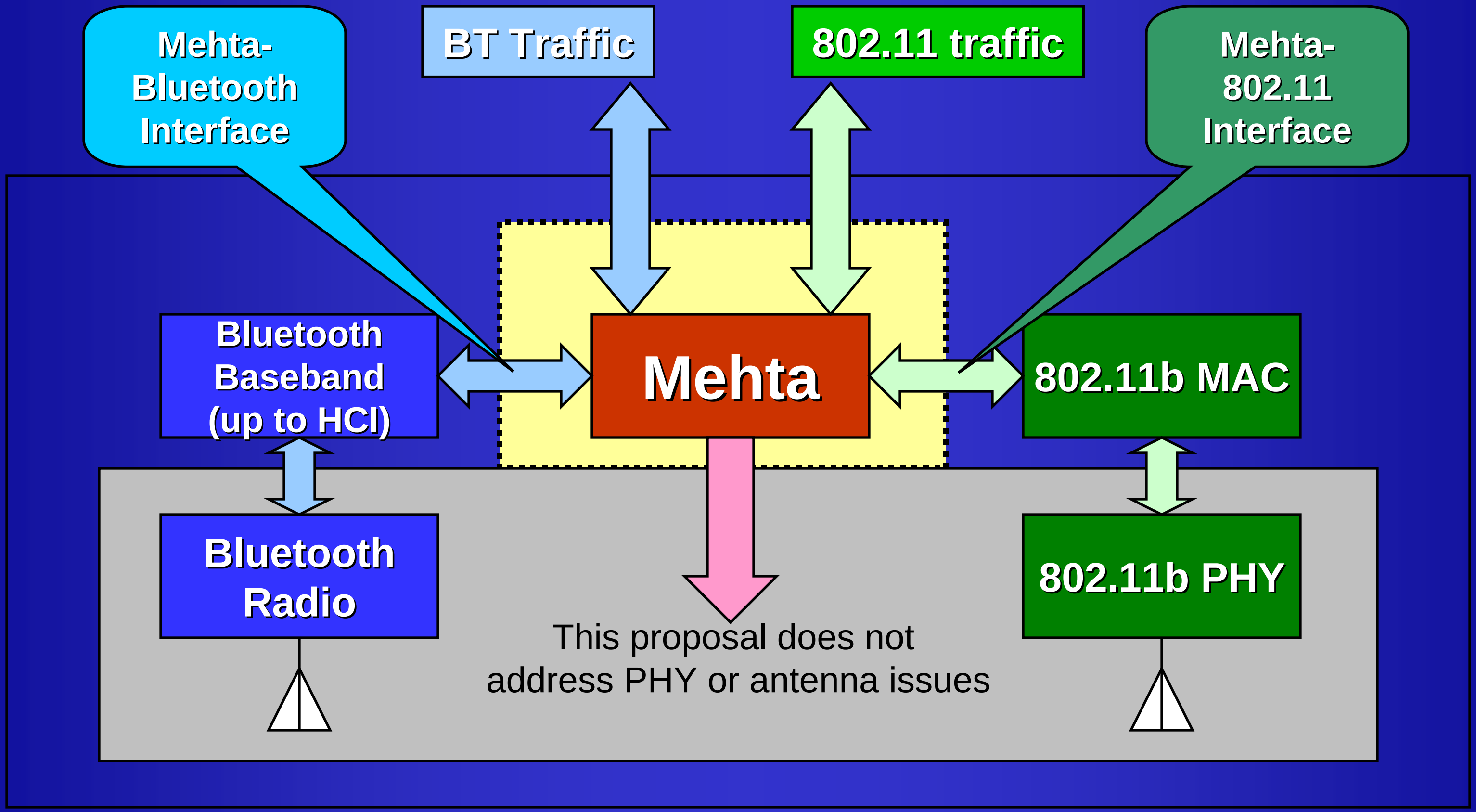
Model II

- ***Adaptive data rate*** can lower the effective data rate when collisions occur and the re-transmission counters are high; however, higher data rate leads to shorter packet duration which is better in the presence of interference; the data rate scaling algorithm for 802.11 is not part of the standard and the user might need to set the data rate at a fixed rate as high as possible
- ***Adaptive flow control*** can facilitate the avoidance of multiple collisions when a continuous block of noisy channels is coming up

Model III

- Use SNIR values from the physical layer as a time-slot distribution among the users so that the system throughput is maximized
- To combat unfairness issues, use linear programming algorithms and generalizations of existing router-scheduling algorithms
- **Note:** Linear programming methods are iterative and there is no upper limit for the number of operations required

“Mehta Engine”
MAC EnHanced Temporal Algorithm



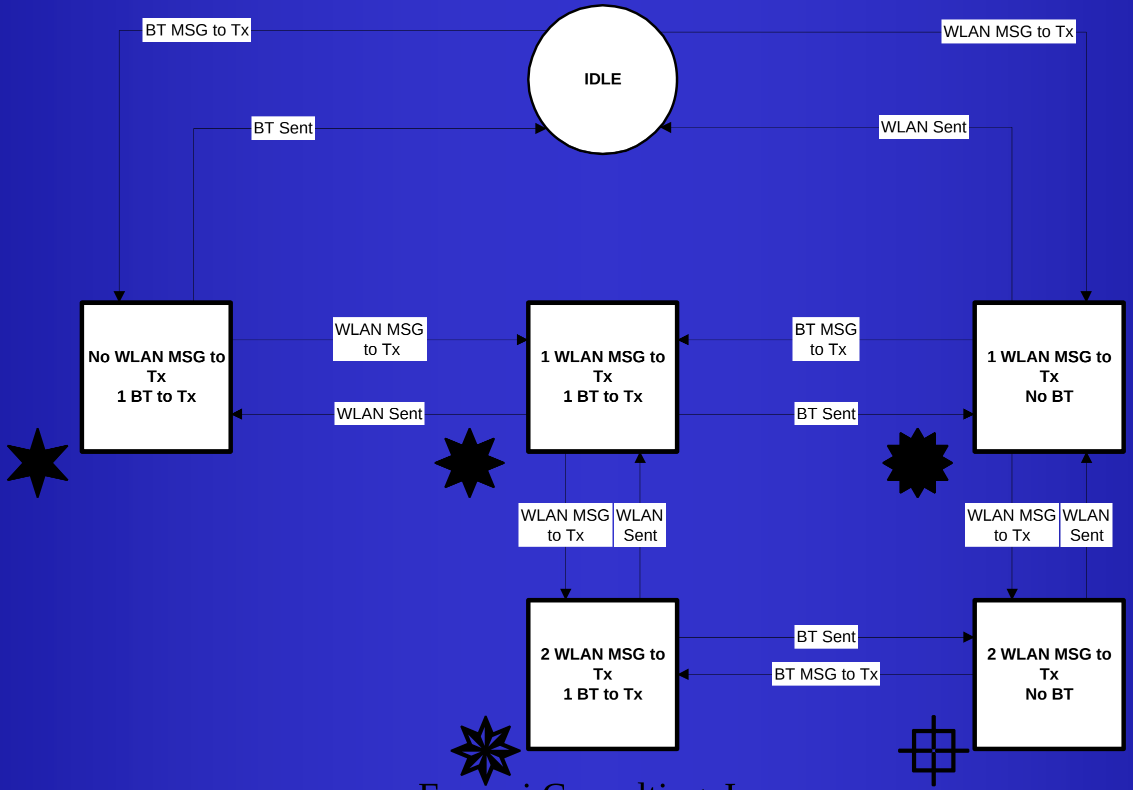
This proposal does not address PHY or antenna issues

Mehta: Top level overview

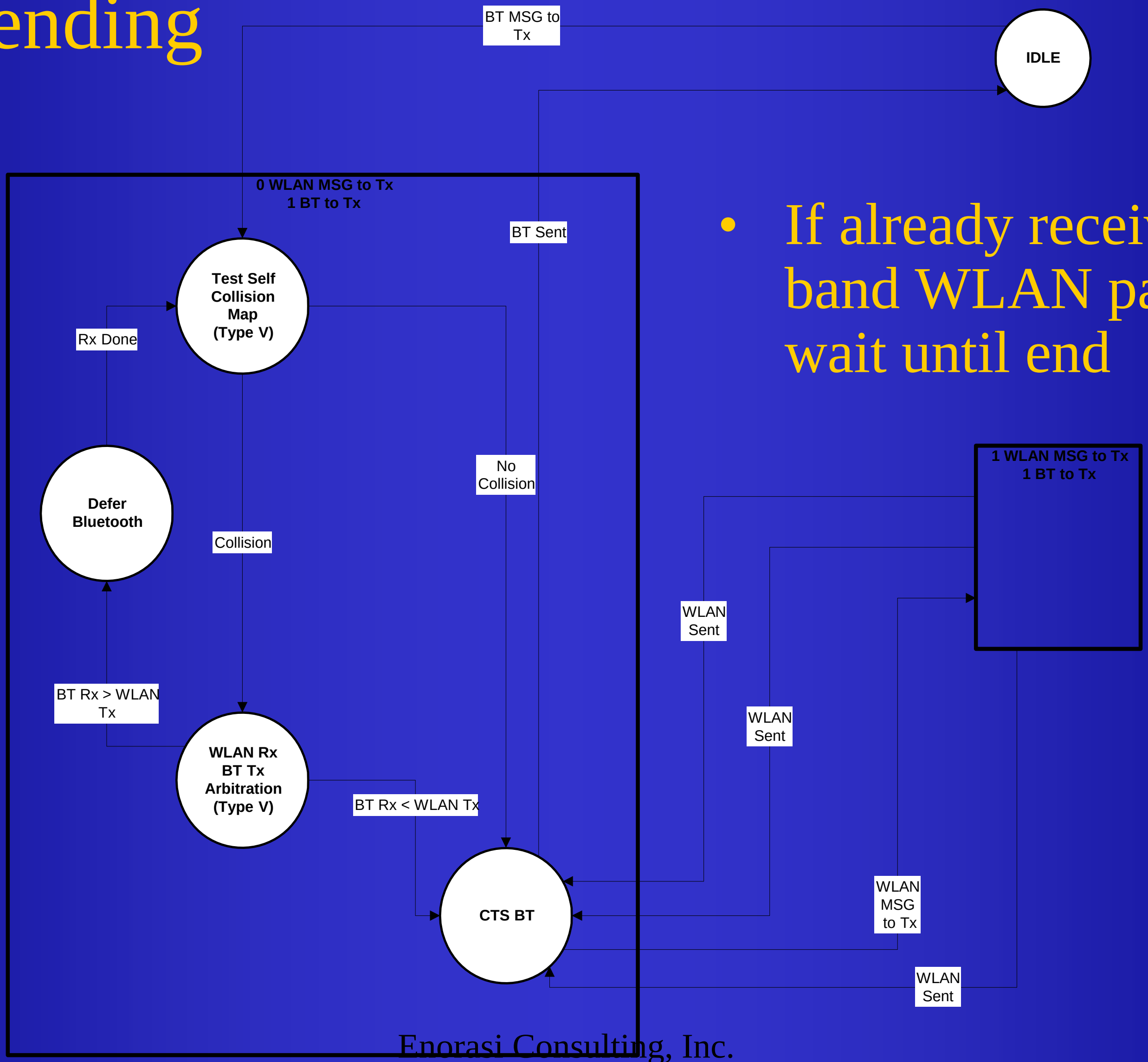
- Assumes independent RF systems
  - Receivers and transmitters share different antennae
  - No RF isolation assumed, however
- Observes traffic patterns in both systems
  - Monitors BT for ACL or SCO
  - Monitors 802.11b for beacons, MPDU, ACK, etc
- Interface allows flow of data and control information
  - Allows exchange of 802.11b channel boundary
  - Allows exchange of BT FHS and clock offset
    - Same interface concept could be used for BT-BT coordination, if FCC rules are changed to permit
- Optimizes timing and duration of traffic
  - MAC layer coordination allows precise timing of packet traffic
  - 802.11b packets can be squeezed between in-band BT slots
  - Packet sizes in 802.11b not especially important; 750 byte MPDU is used in this proposal

Mehta State Machine

- In the overall state machine, 5 sub machines need to be described
  - State machine actions depend on current traffic and number of messages in queues

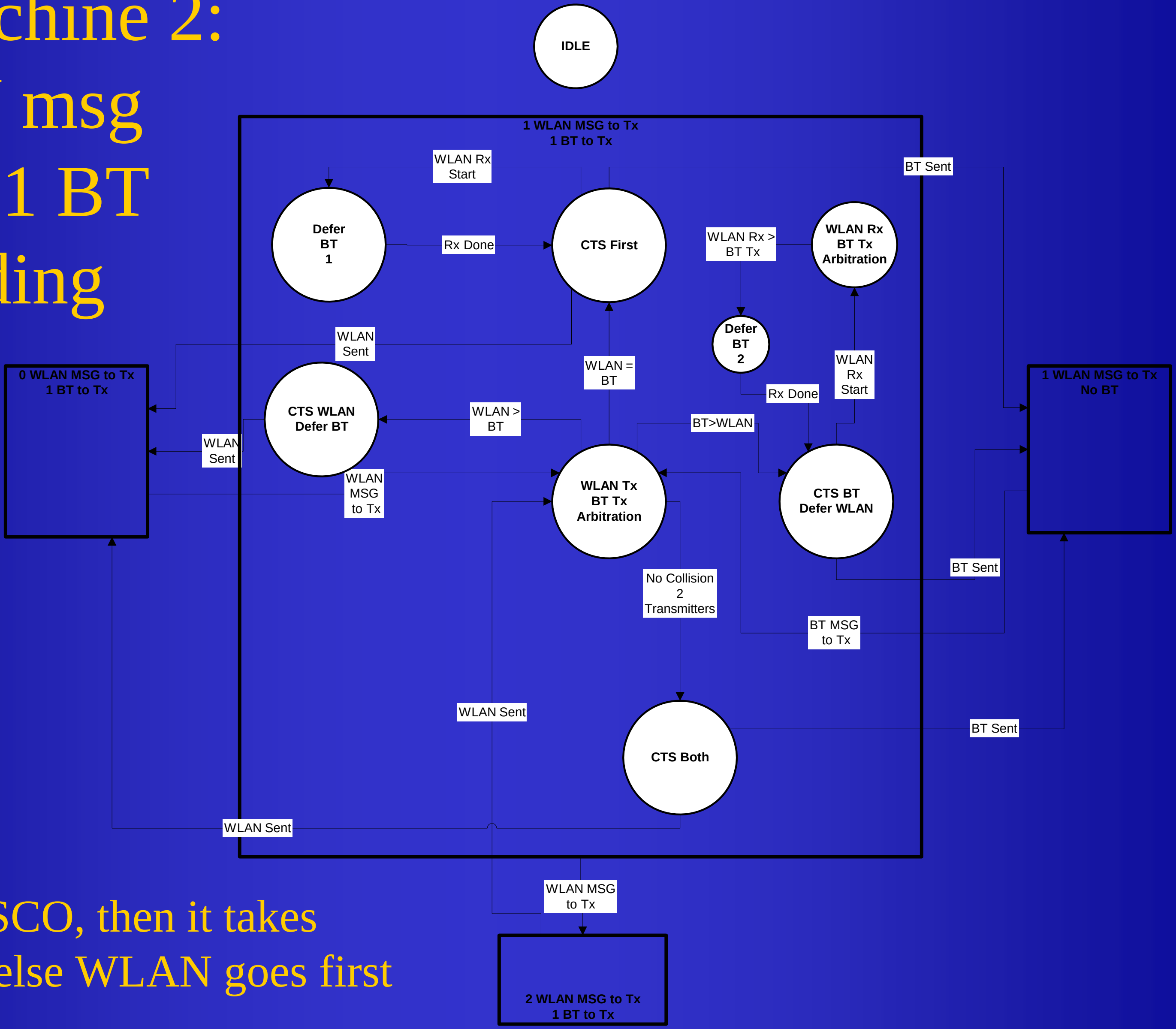


State Machine 1: BT pending



- If already receiving in-band WLAN packet, wait until end

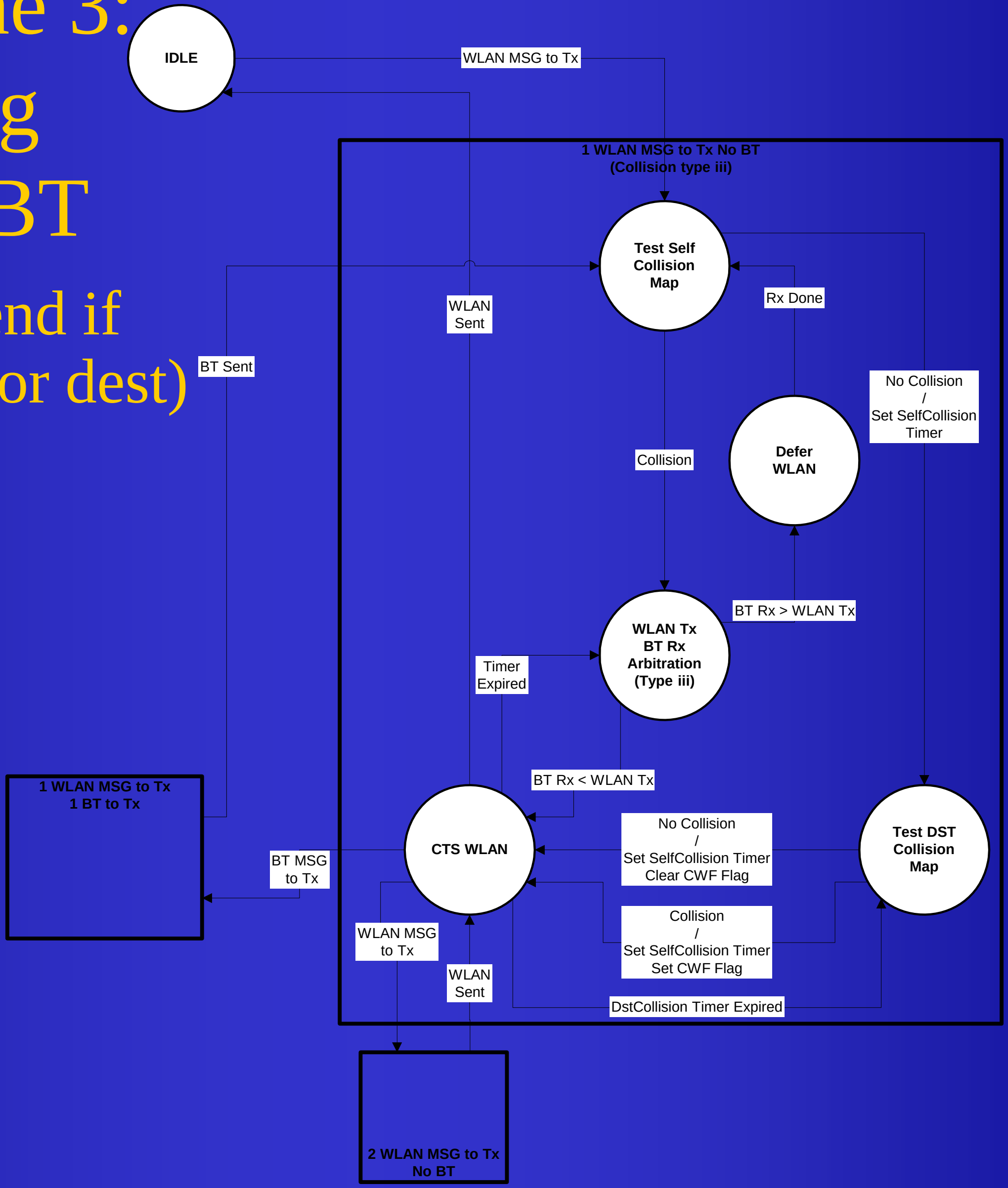
State Machine 2: 1 WLAN msg pending, 1 BT msg pending



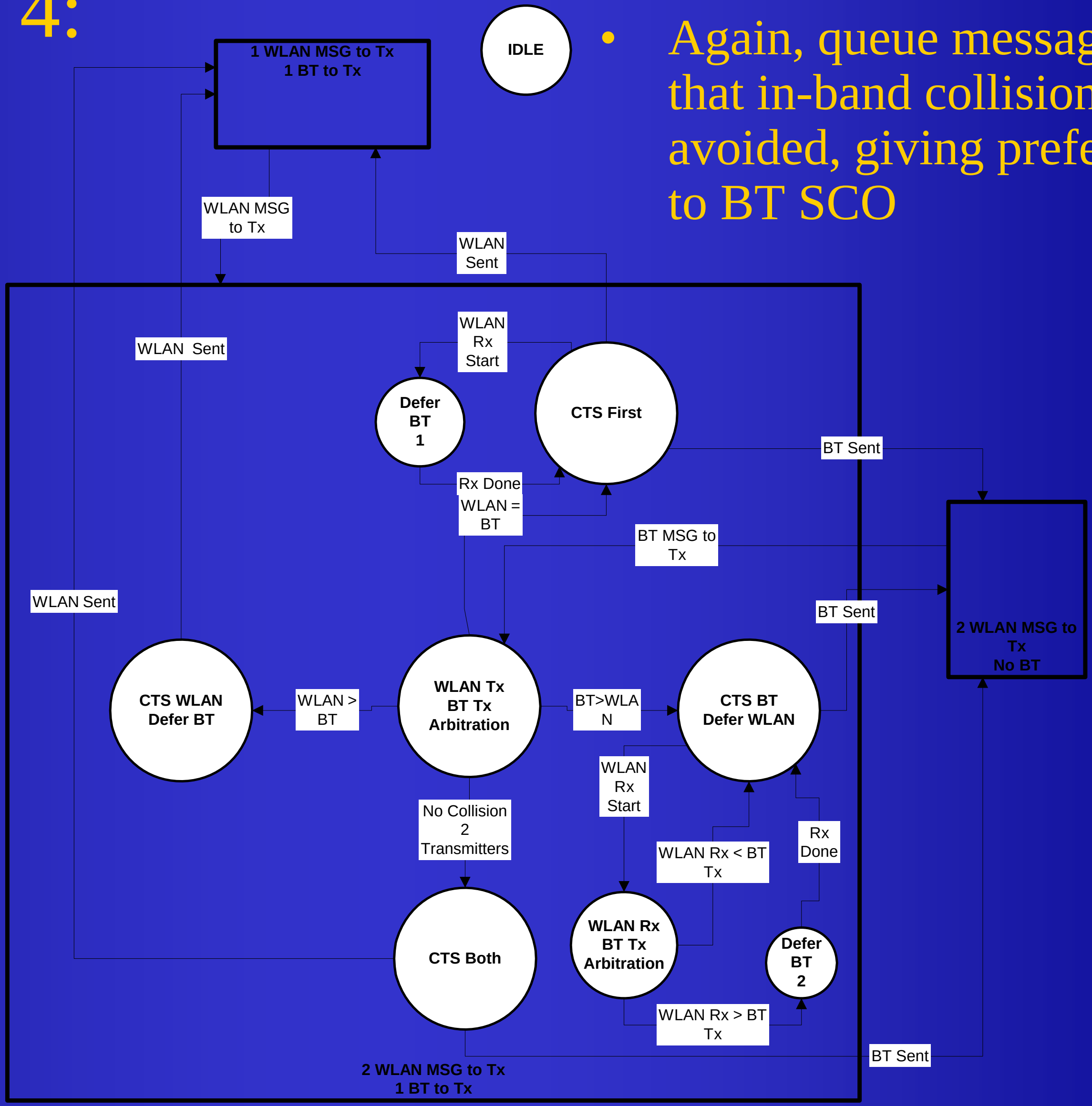
- If BT is SCO, then it takes priority; else WLAN goes first

State Machine 3: 1 WLAN msg pending, no BT

- Wait for BT to end if in-band (source or dest)

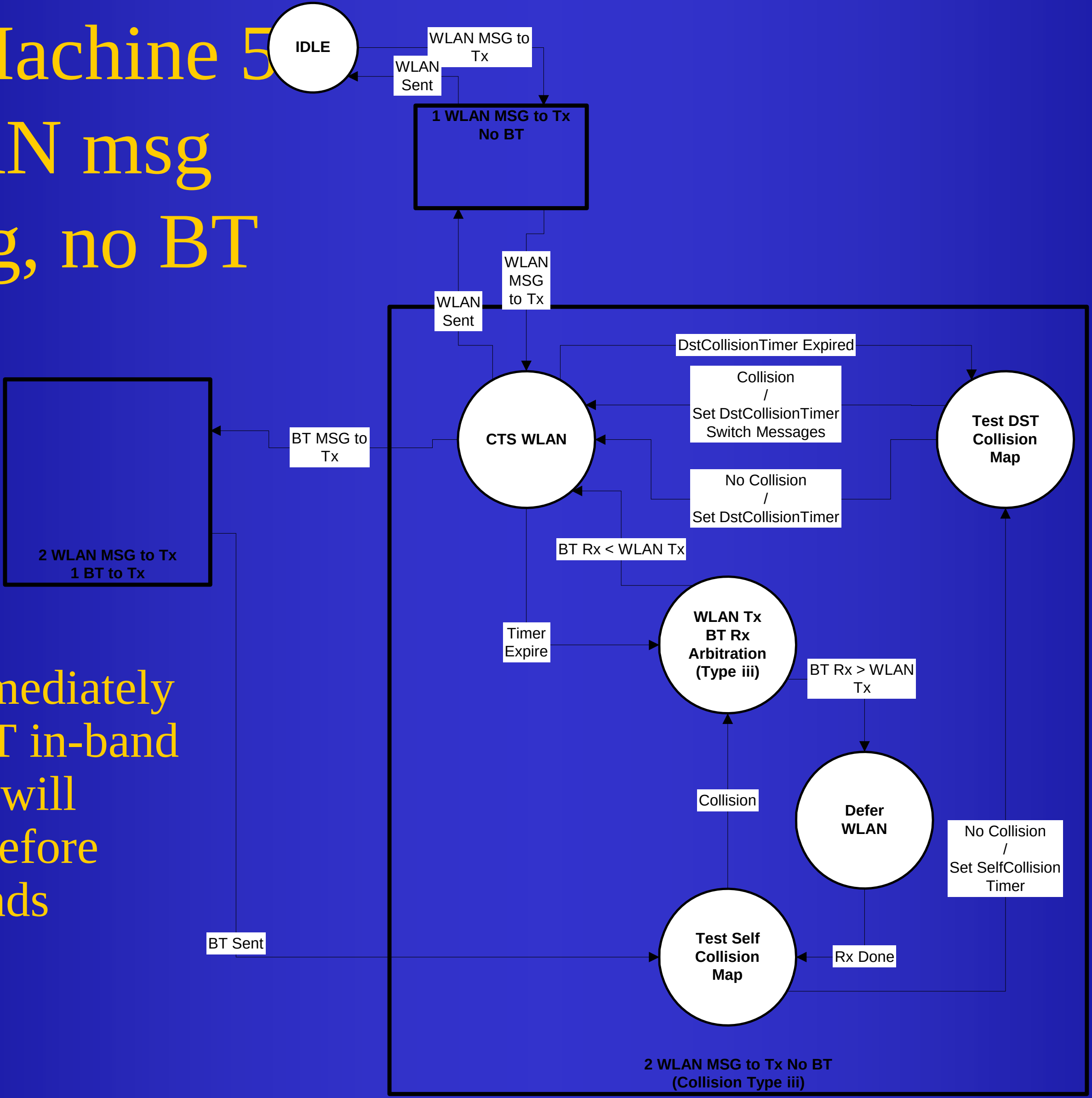


State Machine 4: 2 WLAN msg pending, 1 BT msg pending



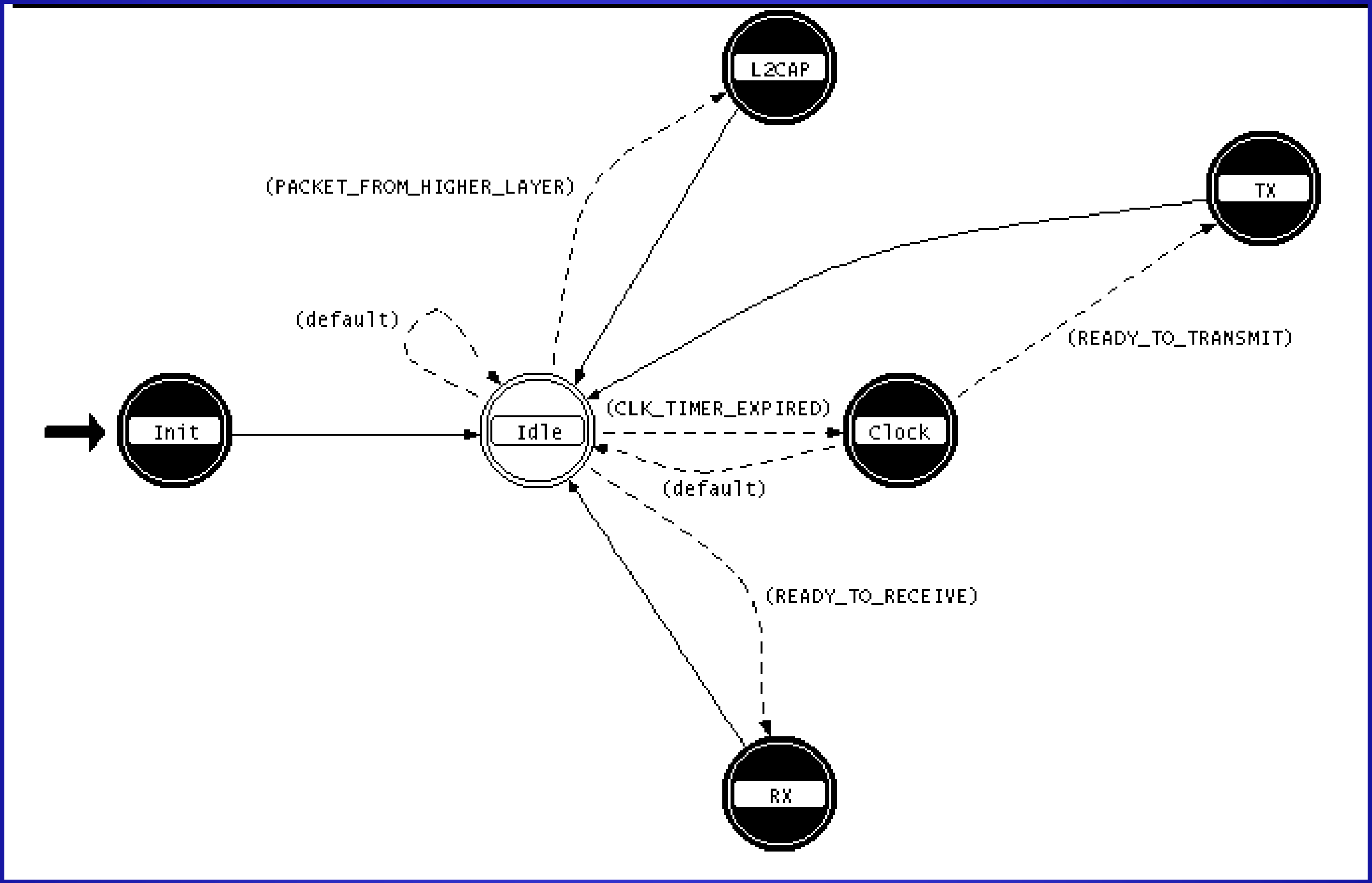
- Again, queue messages so that in-band collisions are avoided, giving preference to BT SCO

State Machine 5
2 WLAN msg pending, no BT

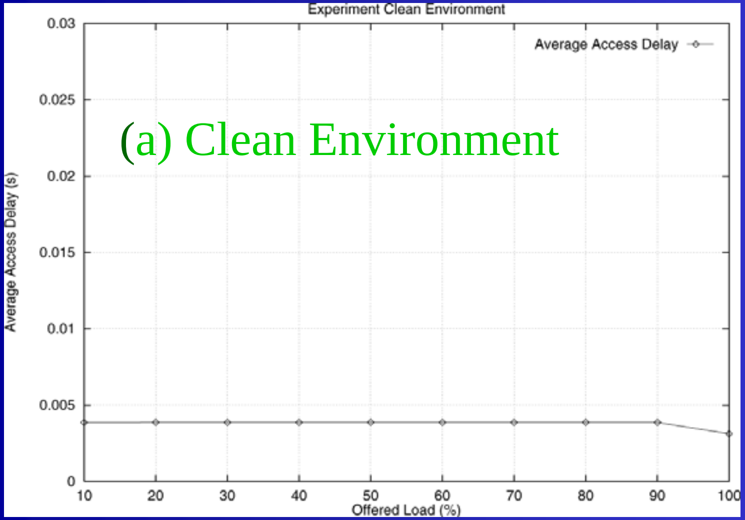


- Send immediately unless BT in-band collision will happen before packet ends

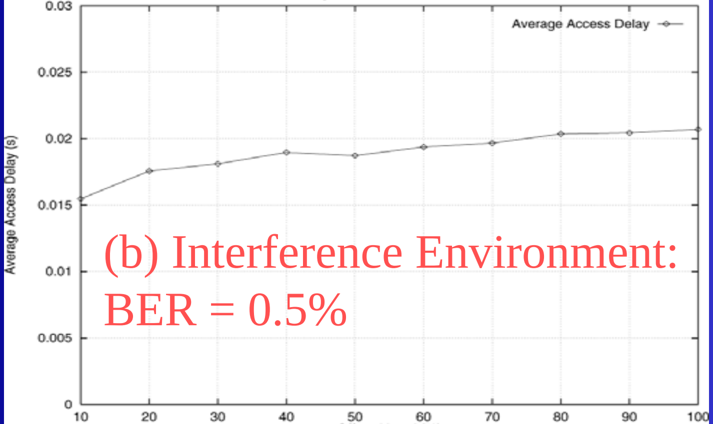
Bluetooth MAC Model



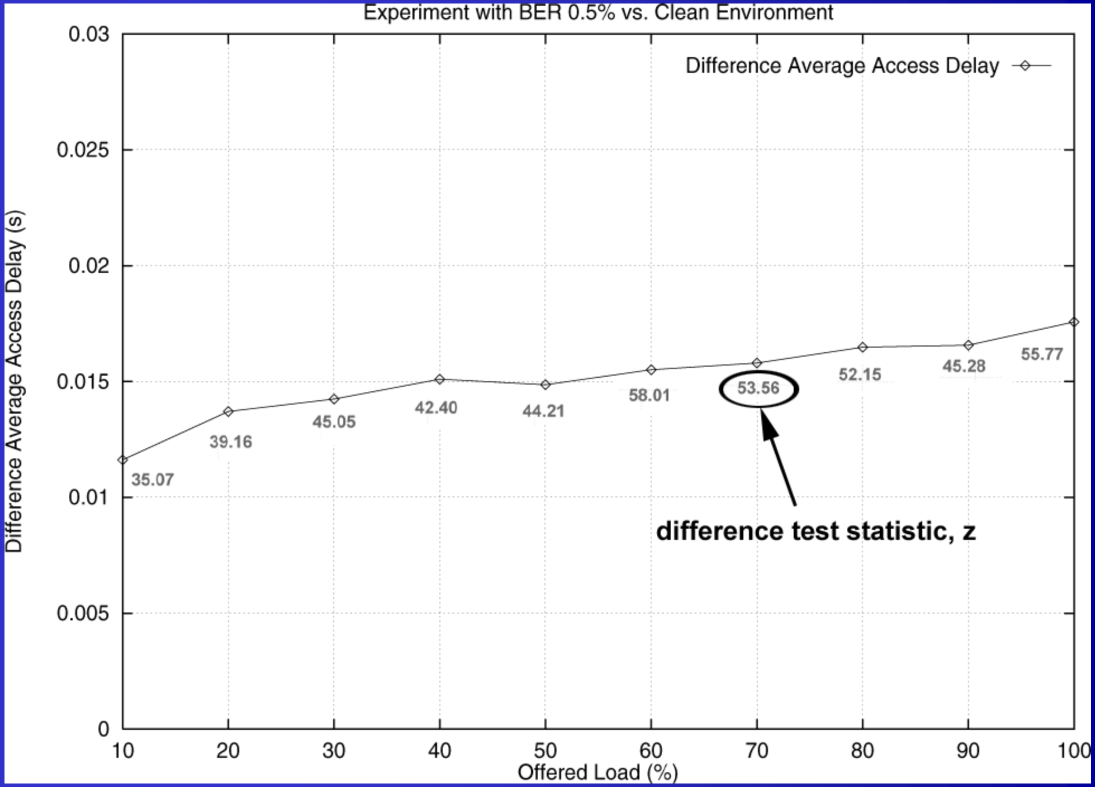
Measurement Example



(a) Clean Environment



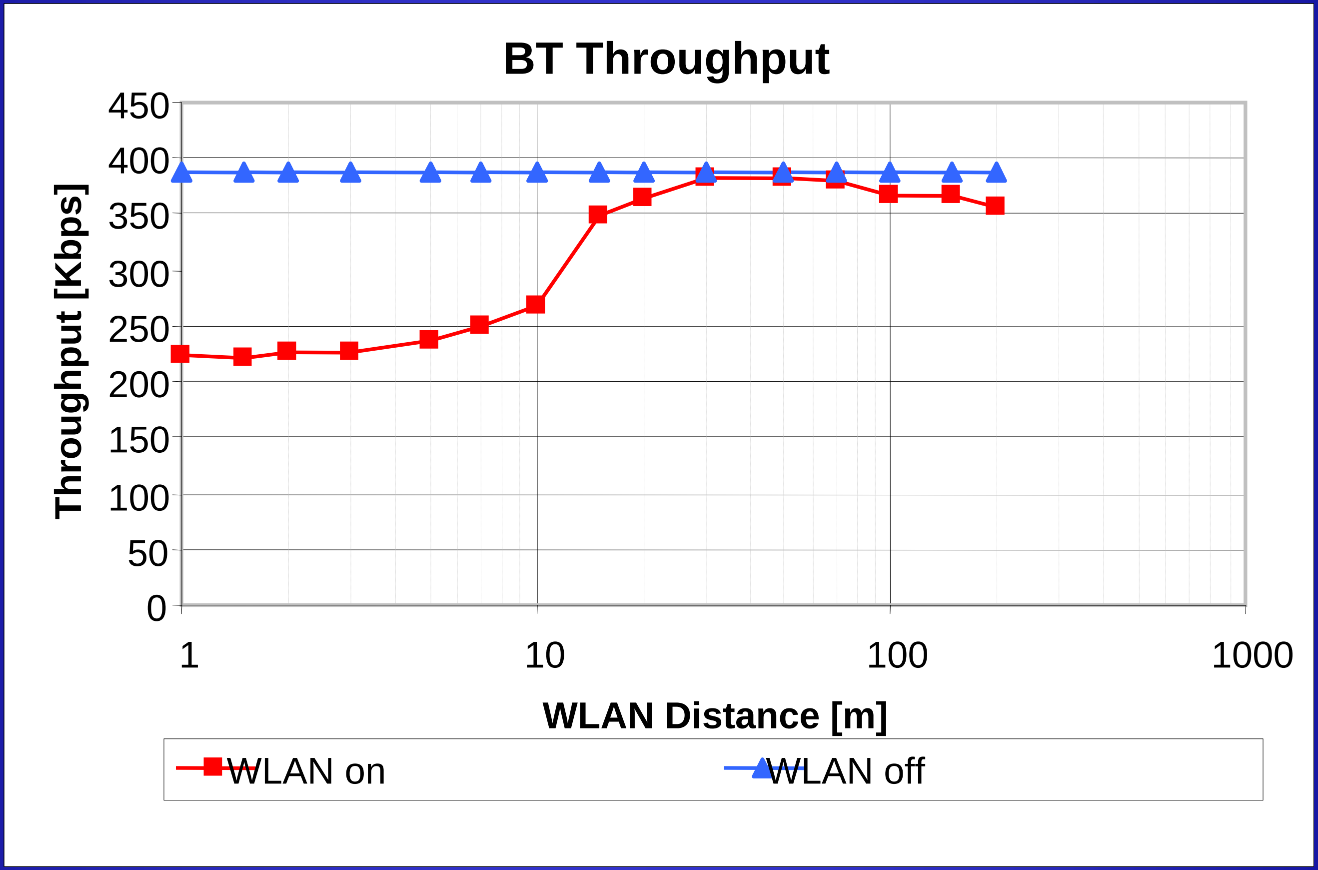
(b) Interference Environment: BER = 0.5%



difference test statistic, z

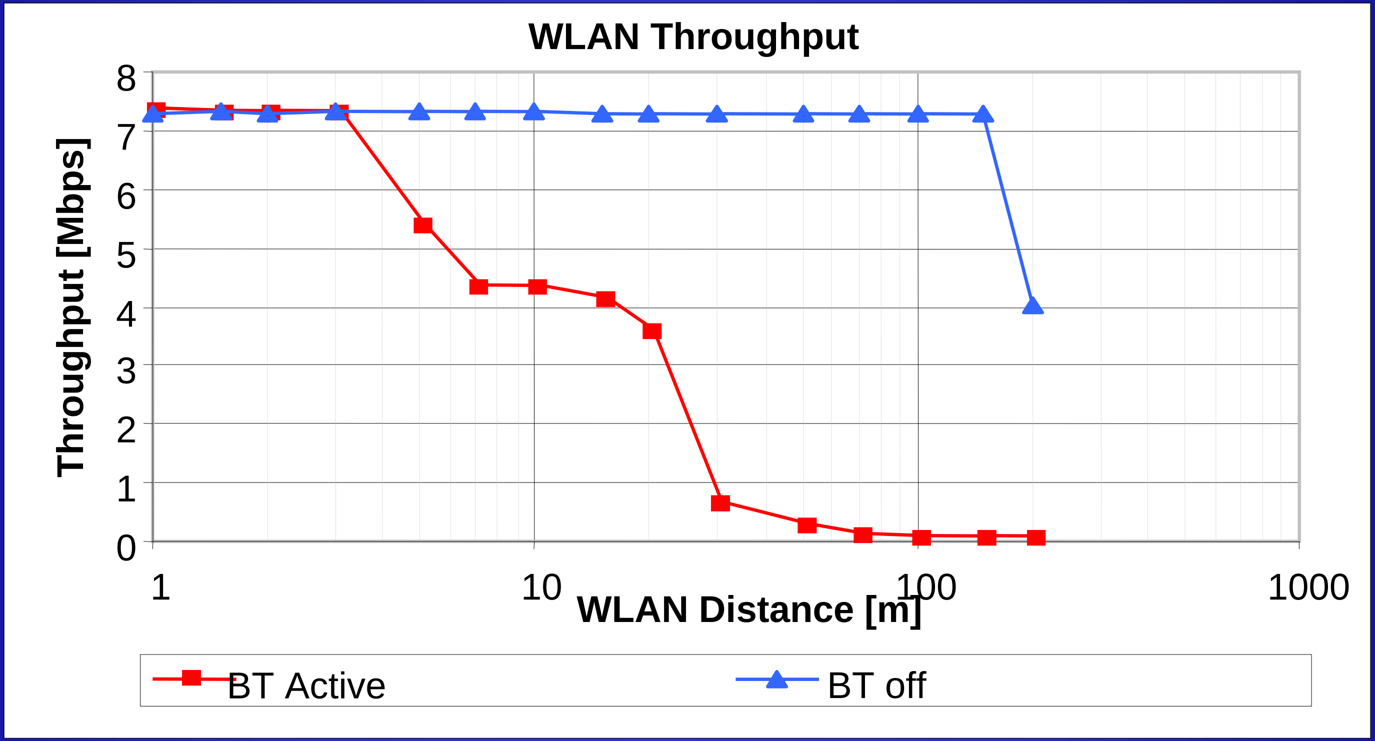
Difference Measurement

Preliminary Simulation Run(1)



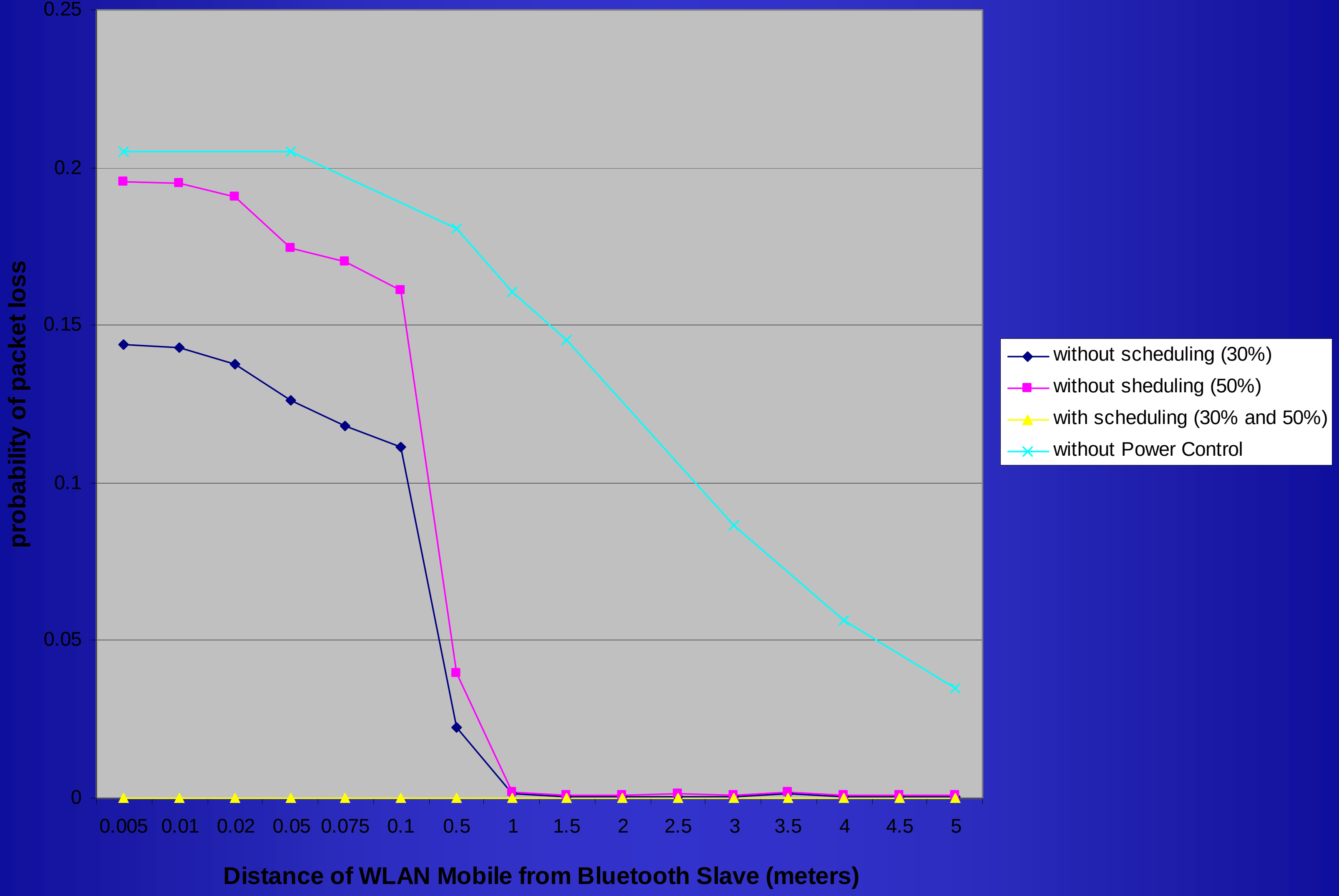
- Asymmetrical traffic AP->STA

Preliminary simulation run(2)

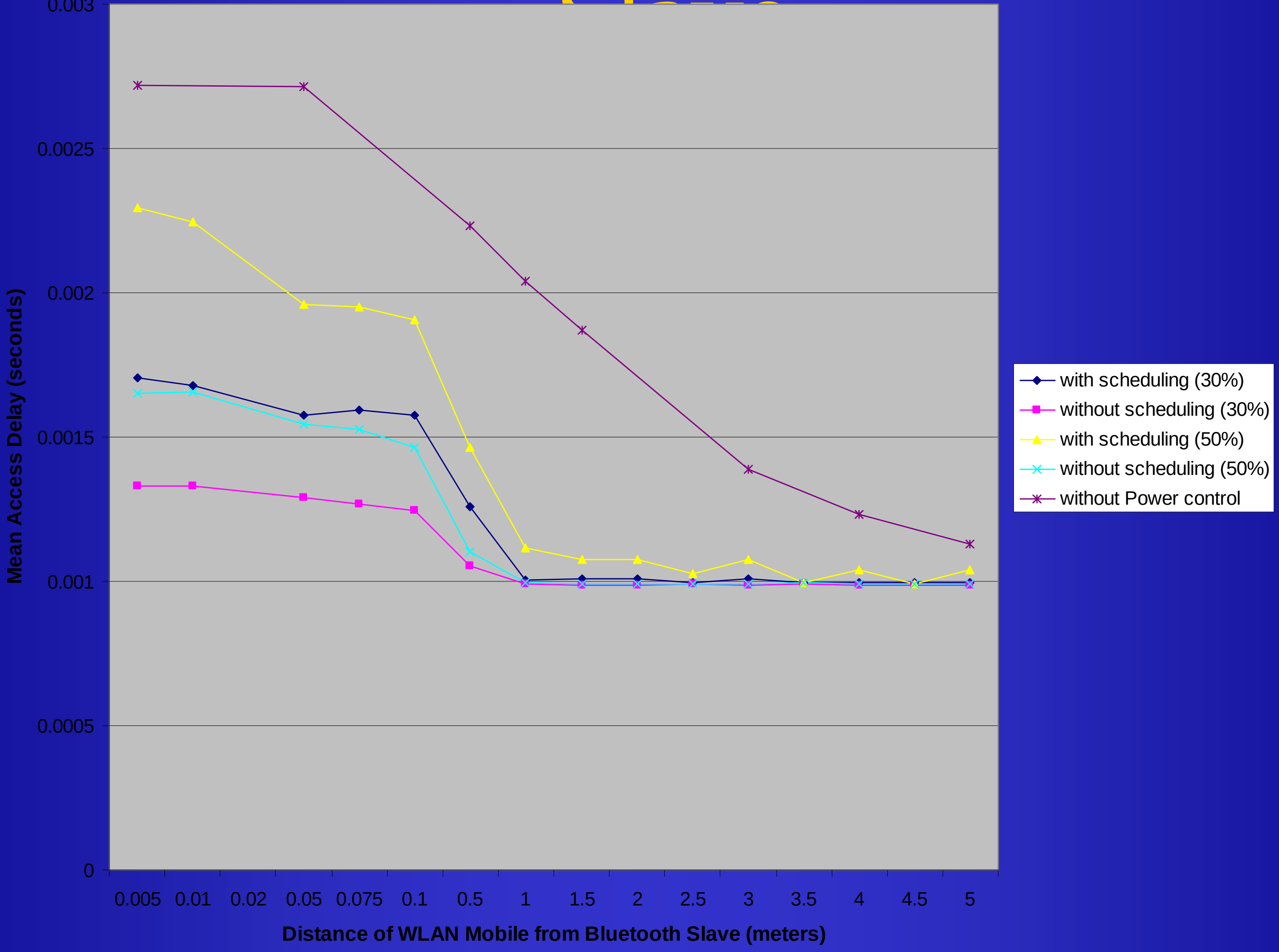


- Throughput at top of MAC (PHY)
- BT2 distance 1 meter
- STA to BT1 distance 10 cm

Packet Loss at Bluetooth Slave



Mean Access Delay for Bluetooth Slave



Data Traffic Models

Performance Metrics

- Bit/Packet Error Rate at PHY/MAC
- Data Throughput/Goodput
- Data Latency (one-tailed test)
- Data Jitter

Performance Issues

- At which layer should we measure error rate, throughput, delay, jitter ?
- The duty cycle used has a big impact on the results produced; the end client should be able to test the performance impact according to its particular needs
- What about asymmetric traffic patterns ?

Input Models

- Statistical descriptions of the data traffic source
- Periodic data source like voice in Bluetooth
- Poisson source of data

Trace-based Lessons

- Packet error rate increases exponentially with the packet size; regression analysis shows that packet error rate doubles for every 300-byte increment of the packet size
- Packet error rate increases exponentially with distance; regression analysis shows that packet error rate doubles for every increase of 17 feet
- Packet error rate increases 30% at a speed of 5 feet per second

Conclusions

- For BT-802.11 distances over 2 meters
  - Coexistence not really an issue
  - Not a practical usage model
- For BT-802.11 distances 0.5-2 meters
  - Interference is significant
  - Collaboration may be difficult to implement
  - Non-collaborative mechanisms provide a good solution
- For co-located BT-802.11
  - Interference most severe; throughput can be nil
  - Collaboration is feasible and can offer great performance improvement

Conclusions (cont.)

- The 2.4GHz band is over-populated!
- All new devices in the 2.4GHz band should consider coexistence issues from the moment of their initial design
- Everybody has to contribute if we do not want to end up with another ***garbage*** band

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