Coexistence in Unlicensed Bands: Challenges and Solutions

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What This Tutorial is About

- How to evaluate the effects of interference on performance
  - Step by step procedure
  - Three different methodologies
  - Several case study examples
  - Insights on factors to consider
- How to go about developing coexistence mechanisms
  - Expectations
  - Major roadblocks

We won't cover

- Signal processing and communication theory
  - How to design receivers, filters, other anti-jamming techniques
- What the instructor does not know
  - Any specific product implementation

Overview

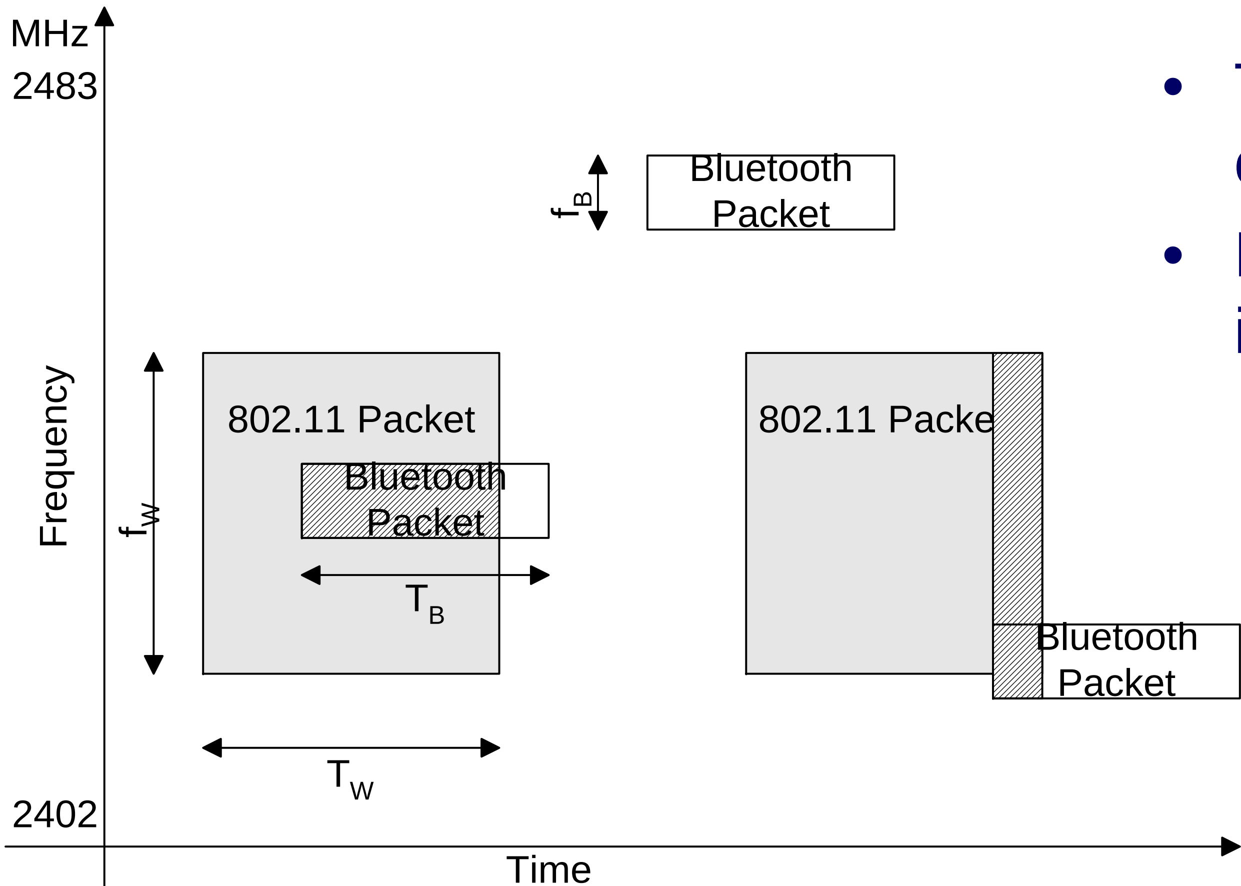
- What is the problem?
  - Motivations and objectives
  - Wireless technologies survey
- How to approach performance analysis?
  - Step by step methodology
  - Metrics, usage scenarios, applications
- Wireless technology protocol overview
  - IEEE 802.11, Bluetooth, Zigbee
- Simulation modeling
  - Building a coexistence modeling platform
  - Results
- Interference Analysis
  - Case study for deriving a probability of packet collision
- Experimental Validation
  - Tying it all together

More Overview

- Coexistence Mechanisms Elements
  1. Channel estimation
  2. MAC layer protocol behavior
  3. Channel selection
  4. Modulation
  5. Protocol collaboration

Motivation

- Many wireless technologies use unlicensed bands so coexisting wireless networks can suffer significant mutual interference and performance degradation



- Time and frequency collision.
- Different types of interferers:
  - Frequency Hopping: Bluetooth, 802.11
  - Direct Sequence Spread Spectrum: 802.11b

Objectives

1. Quantify the impact of mutual interference on the protocol performance
   - MAC and PHY models or alternatively implementation prototypes to describe the protocol behavior
   - Relevant usage scenarios and applications with input parameters of topology, transmit power, and traffic distribution
   - Performance metrics: bit error rate, packet loss, access delay, throughput

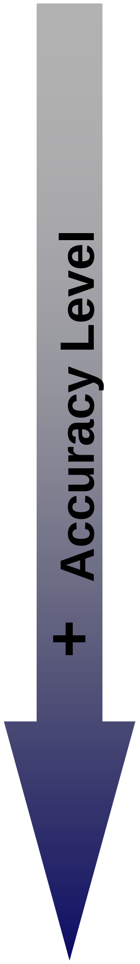
2. Develop coexistence mechanisms to reduce mutual interference
   - MAC layer solutions typically modify the protocol parameters and options provided
   - PHY layer mechanisms typically require a new design

Later stages of protocol development

Early stages of protocol development

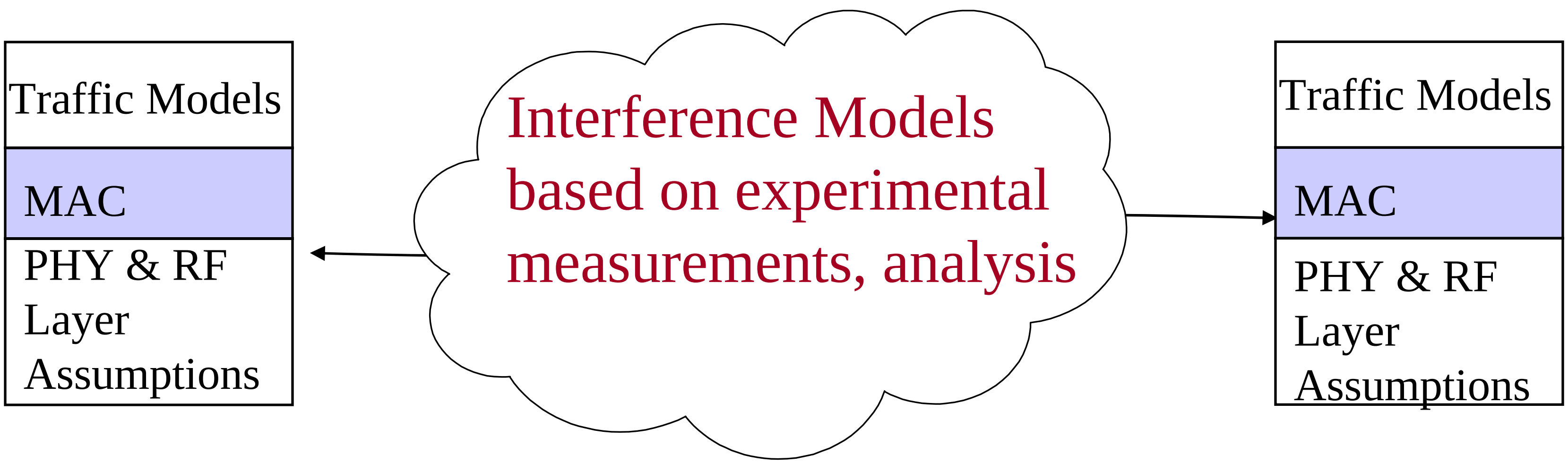
Performance Analysis Methodologies

1. Analytical modeling
   - Availability of vendor fact sheets or theoretical results describing radio receivers in terms of bit error versus signal to interference ratio
   - Based on a probability of packet collision in time and frequency
   - Provide a back of the envelope approximation
2. Simulation modeling
   - PHY and MAC protocol behavior details
   - Study a number of “what if” scenarios
   - Analyze the effects of mutual interference
   - Varying accuracy range
3. Experimental measurements
   - Vendor implementation specific
   - Difficulty tying results to protocol options and parameters



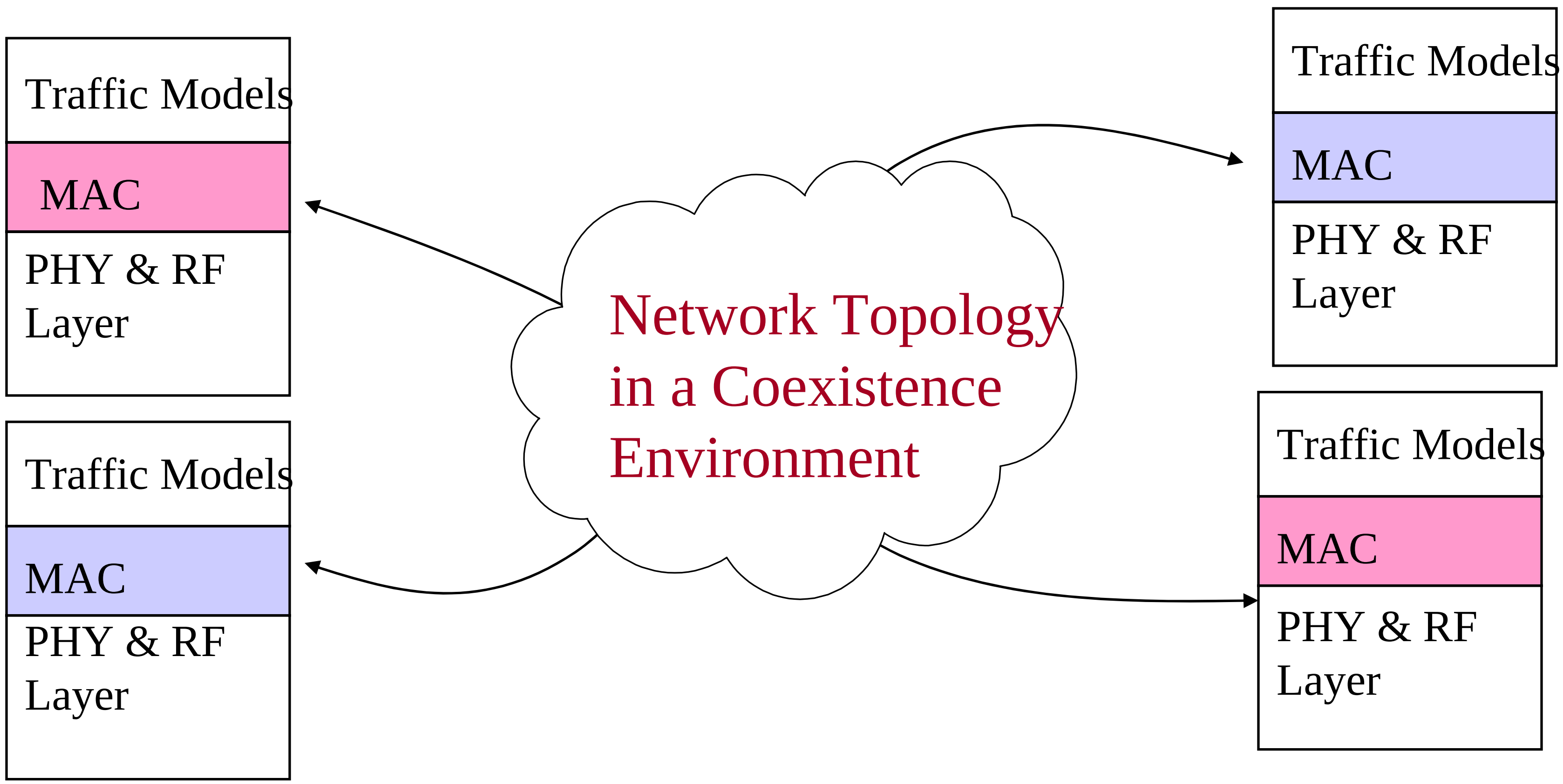
Simulation Model: Approximate Level

- Homogeneous set-up where different devices (BT or 802.11) are considered separately with respect to (accurate) interference models



Simulation Model: More Accurate Level

- Heterogeneous set-up where different wireless devices are co-located within the same environment



Performance Analysis Step-by-step Procedure

1. Scope
   – Define the perimeters of the problem space, for example identify the wireless technologies involved in the study
2. Breadth
   – Define performance metrics
   – List typical usage scenarios including applications and network topologies
3. Depth
   i. Study the protocol behavior
   ii. Configure the parameters
   iii. Analyze the performance
   iv. Validate the results

Coexistence Performance Metrics

- Performance metrics definition
  - Bit Error Rate
  - Packet loss
  - Access delay
  - Throughput
  - Goodput
- Coexistence performance metrics:
  - Compare each specification against itself
  - Difference of two independent sample means: one-tailed hypothesis test
- Where to measure?
- Measurement format

Performance Metrics

- Bit Error Rate: number of bits received in error divided by the total number of bits received
- Packet Loss: number of packets lost due to errors divided by the number of packets successfully received
- Access Delay (seconds): the time it takes to transmit a packet from the time it is passed to the MAC layer until it is successfully received at the destination – generally accounts for queuing and retransmissions delays
- End-to-End Delay (seconds) : the time it takes to transmit an application layer packet *-- generally at the TCP layer*
- Throughput (bits/s): the number of bits successfully received divided by the time it took to transmit them over the medium
- Goodput: the number of successful packets received at the receiver's application layer divided by the number of application layer packets that could be transmitted over the medium

Bit Error Rate

Objective

To measure the number of bits received in error at the destination. This measure is conducted before performing error correction (FEC, HEC)

Note that in a real implementation, this measure is based on a theoretical calculation using the signal to noise ratio measured and the receiver a priori performance. In a simulated environment this can be computed

Definition

- bit error rate: number of bits received in error divided by the total number of bits sent during a period of time. Units:%
- residual errors: number of bits that remain error after applying an error correction code – theoretical value

Packet Loss

Objective

To measure the number of packets discarded at the MAC layer due to errors in the bit stream. This measure is conducted after performing error correction (FEC, HEC)

Definition

- packet loss: number of packets lost divided by the total number of packets sent during a period of time. Units:%

Access Delay

Objective

To measure the time it takes to transmit a packet from the time it is passed to the MAC layer until it is successfully received at the destination (MAC layer)

Definitions

- average access delay: sum of all access delays divided by the number of samples. (Units = milliseconds)
- coefficient of delay variance: access delay standard deviation divided by the average access delay
- access delay probability distribution function (95th, 99th percentiles)

End-to-end Delay

Objective

To measure the time it takes to transmit a packet from the time it is passed to the TCP layer until it is successfully received at the destination (TCP layer). This is the delay observed from the application's perspective

Definitions

- average end-to-end delay: sum of all end-to-end delays divided by the number of samples. (Units = milliseconds)
- coefficient of delay variance: end-to-end delay standard deviation divided by the average end-to-end delay
- delay probability distribution function (95th, 99th percentiles)

Throughput

Objective

To measure the number of bits per second delivered over the medium. This measure includes both packet payload and headers

Definition

- average throughput: total number of bits received at the destination divided by a unit of time.Units: Mbit/s

Goodput

Objective

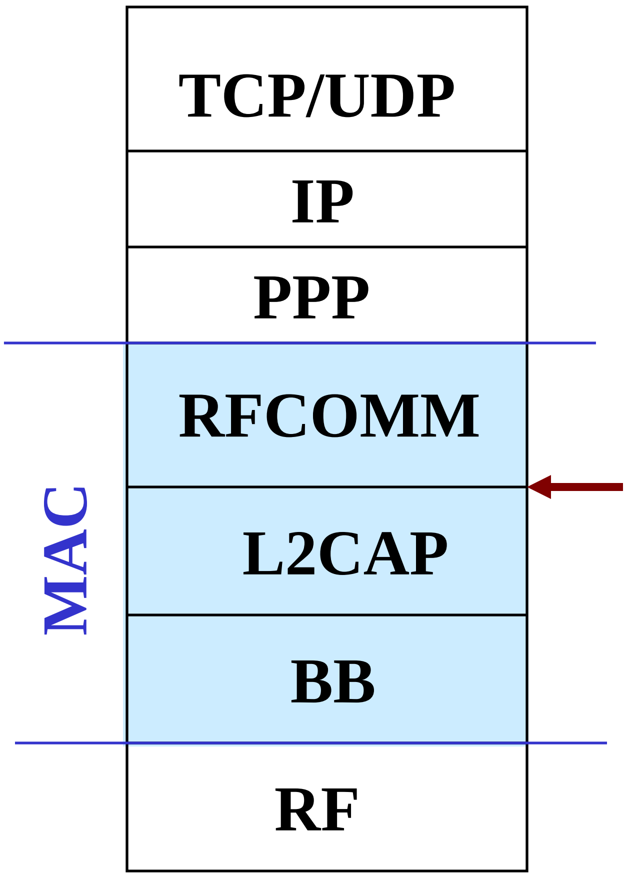
To measure the number of bits of information delivered over the medium. This measure does include neither packet headers nor overheads. This may be useful for measuring the performance of higher layer traffic

Definition

- average goodput: total number of information bits received at the destination divided by a unit of time. Units: Mbit/s

Where to measure performance?

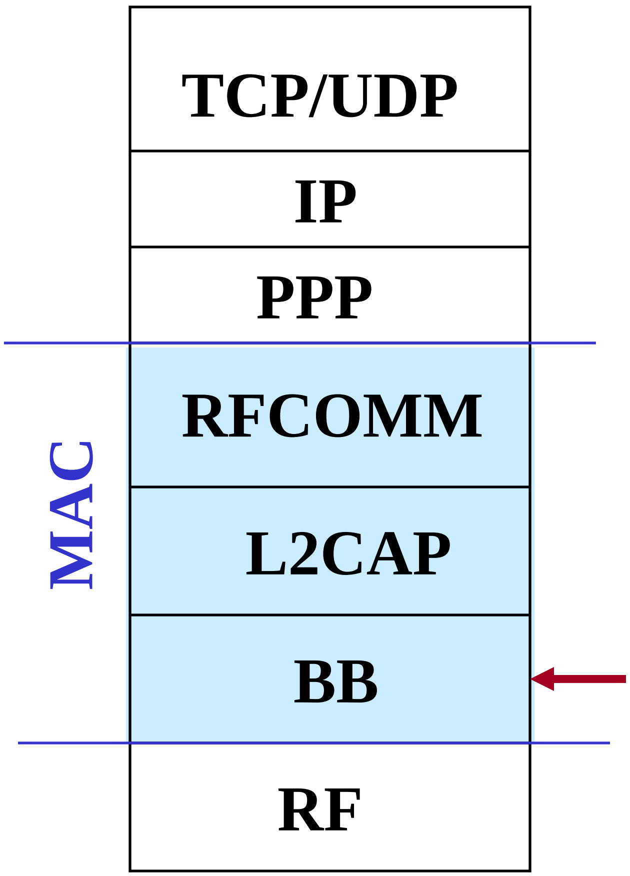
Example: Bluetooth LAN Access data traffic flow



- Access delay is computed after the reassembly of DM3 and DM5 packets into an L2CAP packet and may include retransmission time due to ARQ
- HEC, FEC and CRC are performed on the DM3 and DM5 packets received
- Throughput includes L2CAP overhead
- Goodput includes L2CAP payload only and higher layer overheads

Where to measure performance?

Example: Bluetooth LAN Access data traffic flow



- Access delay is computed upon the arrival of baseband packets containing DM3 and DM5 packets. Therefore the access delay does not account for any retransmission time
- No HEC, FEC and CRC are performed
- Throughput includes L2CAP, DM3/DM5 and baseband packet overheads
- Goodput consists of the transmission of DM5/DM3 packets

Higher layer measurements may give better insights on the impact of interference onto higher layers

Measurement Format

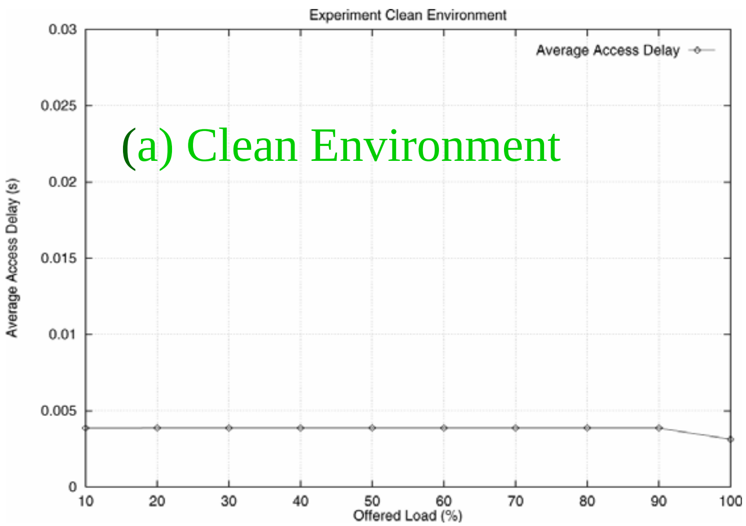
- Map parameters to relevant coordinate axis
- Use either the offered load * or the BER on the x-axis to plot the i) access delay, ii) throughput, iii) goodput, iv) coefficient of delay variation, and v) packet loss on the y-axis

Note: the offered load measures the amount traffic sent as a percentage of the total capacity of the channel. Units: %

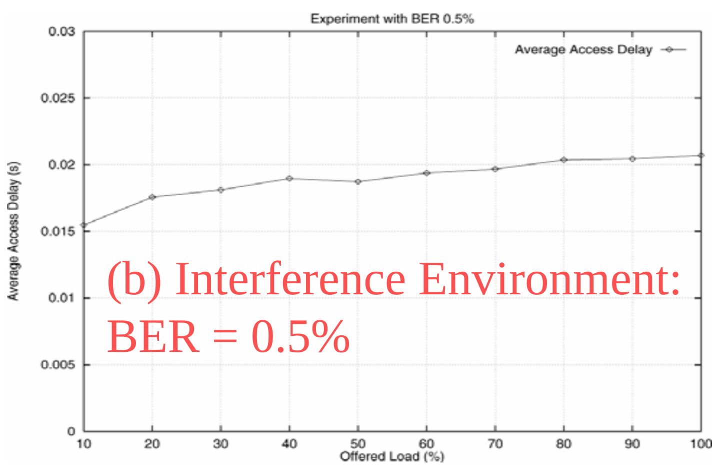
Measurement Methodology

- For every test scenario consisting of a specific network topology (number of devices, distance), and applications (voice, data):
  - obtain performance results for each protocol specification (e.g. IEEE 802.11, Bluetooth) in
    - (a) a clean environment (without interference)
    - (b) a coexistence environment (with the interference effect)
  - compare results from (a) and (b): compute the difference and conduct a one tailed-test on the significance of the difference

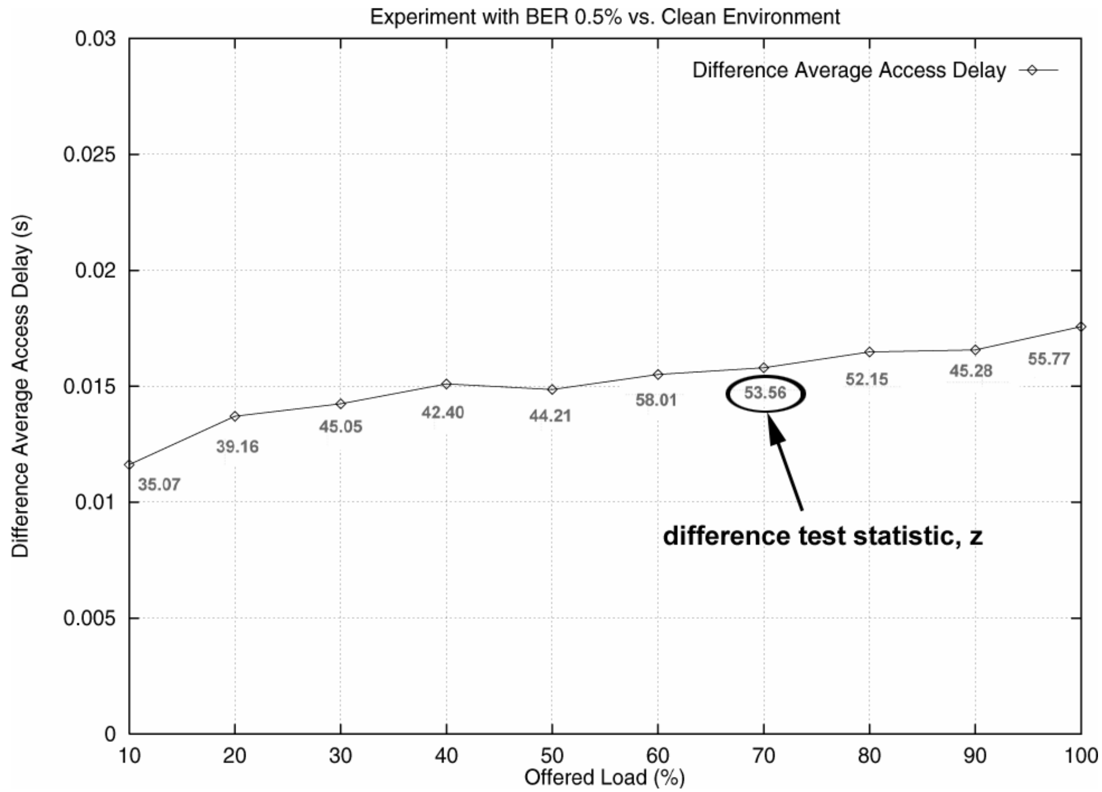
Measurement Example



(a) Clean Environment

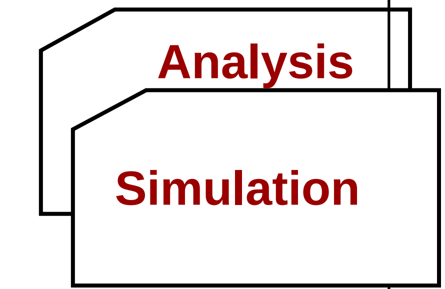


(b) Interference Environment: BER = 0.5%

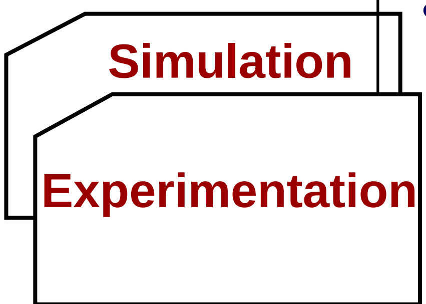


Difference Measurement

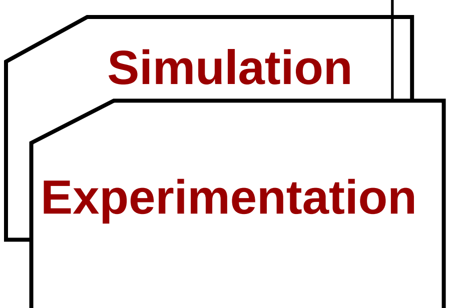
Applications and Traffic Models



- On-Off Model
  - Defines a model for the packet length and interarrival time according to a distribution
  - Focuses on a specific layer and hides the details of higher layer protocols in the stack
  - Useful in controlled experiments where traffic parameters can be isolated and their effects investigated



- Application Profiles
  - Describes application specific parameters such as file, page, frame, encapsulation, etc
  - Captures the mutual interactions and the behavior across all layers of the protocol stack



- Data Traces
  - Obtained from experimental measurements and generally used in simulations
  - Captures the packet types, size, interarrivals resulting from transmission on the medium
  - Perturbations in transmission patterns due to protocol behavior depend on the experiment conducted

Coexistence Methodology

Case Study Evaluation

- Three wireless technologies are selected:
  IEEE 802.11b, Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4)
- Evaluate effects of interference on performance
- Identify significant factors to consider
- Investigate performance trade-offs and scalability issues

Approaches

- Simulation
- Analysis
- Experimental Evaluation

Simulation Modeling

System Simulation Modeling

Packet Level Simulation Module

Traffic Generation

Media Access Control

- **TDMA (Polling, CSMA)**
- **ARQ**
- **FEC / FCS**
- **Frequency Channel Selection (Hopping / Spread Spectrum)**
- **Packet collisions (time and frequency)**

INPUT Parameters →

← **OUTPUT Parameters**

DSP Module (developed by others at NIST)

Transmitter / Receiver

Modulator/ Demodulator

Channel Propagation

BER Computation

PHY layer function BER_COMPUTE()
is called at the end of every packet transmission

INPUT Parameters:

- Packet bit sequence
- For all packets in transmission:
  Signal Type, Transmission Power, Frequency, Packet Start Transmission Time, Packet End Transmission Time, Distance between transmitter and receiver node

OUTPUT Parameters:

- Packet bit sequence with errors (bits flipped)

Channel Modeling

- Additive White Gaussian Noise, multipath fading
- Path loss model

$$Lp = \begin{cases} 32.45 + 20\log(f.d) & d < 8m \\ 58.3 + 33\log(d/8) & otherwise \end{cases}$$

- Received power and SIR depend on topology and device parameters:

$$P_R = P_T - L_P$$

$$SIR = P_R - P_I$$

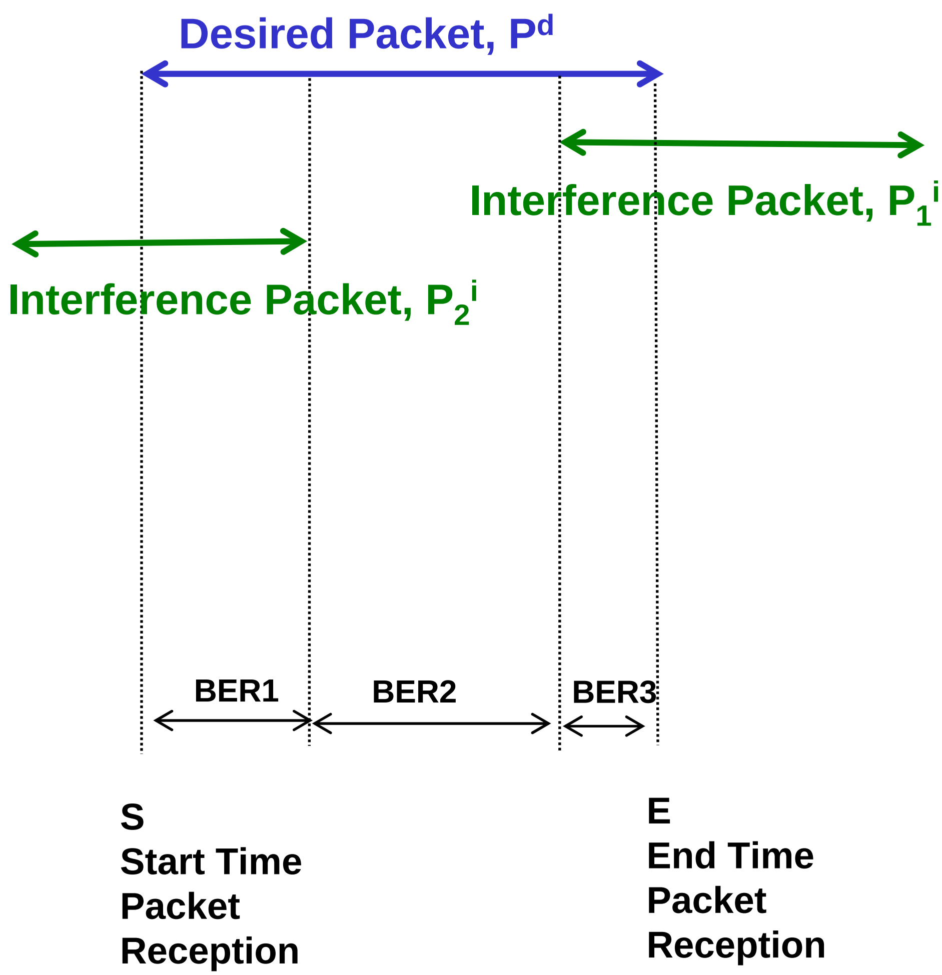
Physical Layer Modeling

- DSP based implementation of transceivers
- Design using typical parameters (goal is to remain non-implementation specific)
- IEEE 802.11
  - Direct Sequence Spread Spectrum (1 Mbits/s)
  - Complementary Code Keying (11 Mbits/s)
  - Frequency Hopping (1 Mbits/s)
- Zigbee
  - Direct Sequence Spread Spectrum
- Bluetooth
  - Non-coherent Limiter Discriminator receiver, Viterbi receiver with channel estimation and equalization

MAC Modeling

- MAC behavioral implementation for IEEE 802.11, Bluetooth, Zigbee
- Frequency hopping
- Error detection and correction
  - Different error correction schemes applied to packet segments (Bluetooth)
  - FCS (802.11)
- Performance statistics collection
  - Access delay, packet loss, residual error, throughput

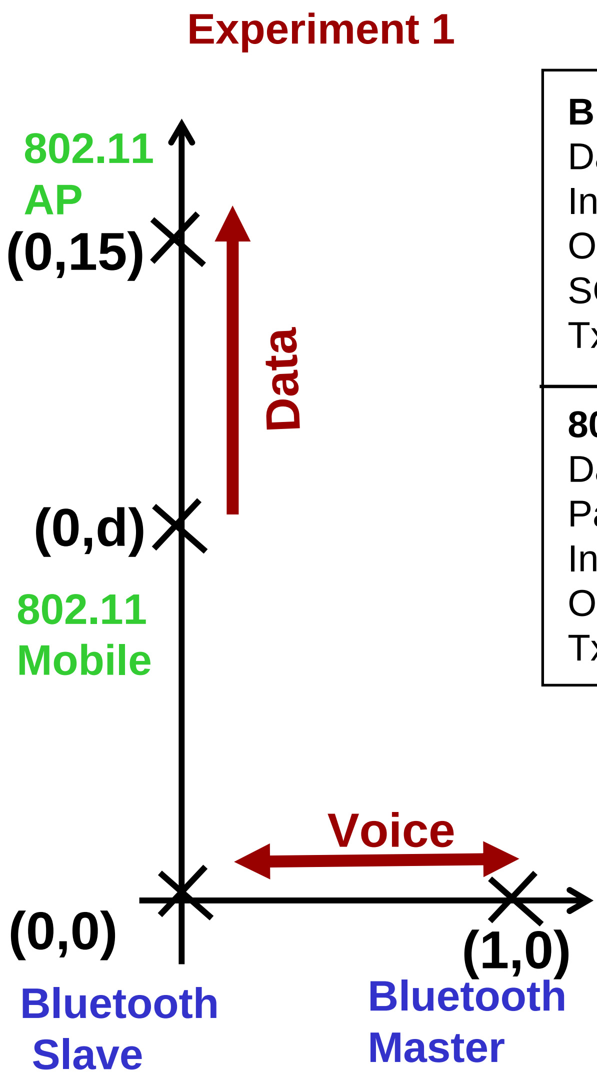
Packet Collisions



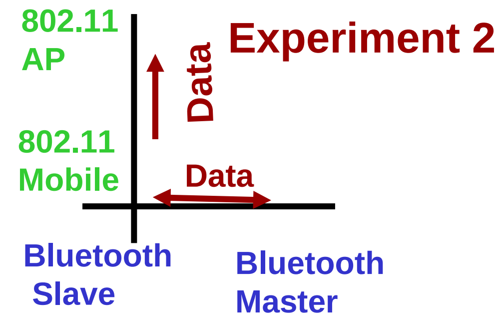
At time E

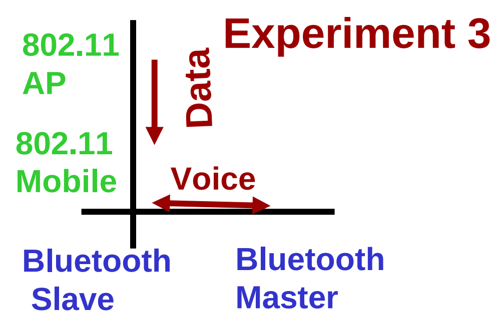
- Desired packet is completely received at its destination
- Parameters of all packets that started/ended in [S,E] is passed to the DSP module to compute BER for each packet segment

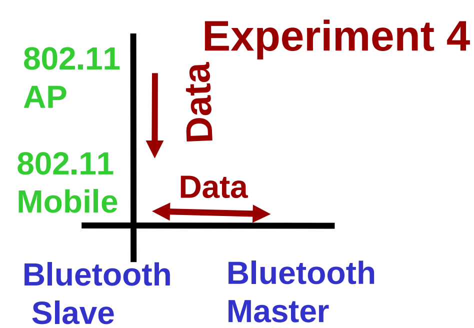
Simulation Topology



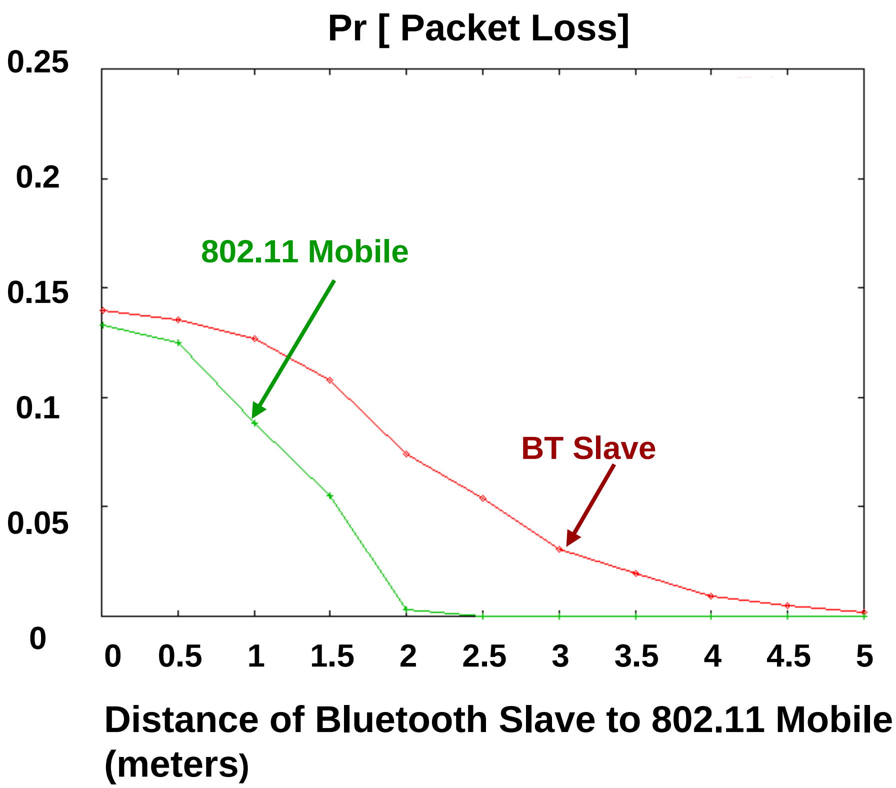
Bluetooth	
Data Packets	DM5, 2871 bits
Interarrival time	20.84 ms
Offered Load	30%
SCO Packets	HV1, 366 bits
Tx Power	1 mW
802.11	
Data Rate	11 Mbits/s
Packet Size	8000 bits
Interarrival time	1.84 ms
Offered Load	50%
Tx Power	25 mW

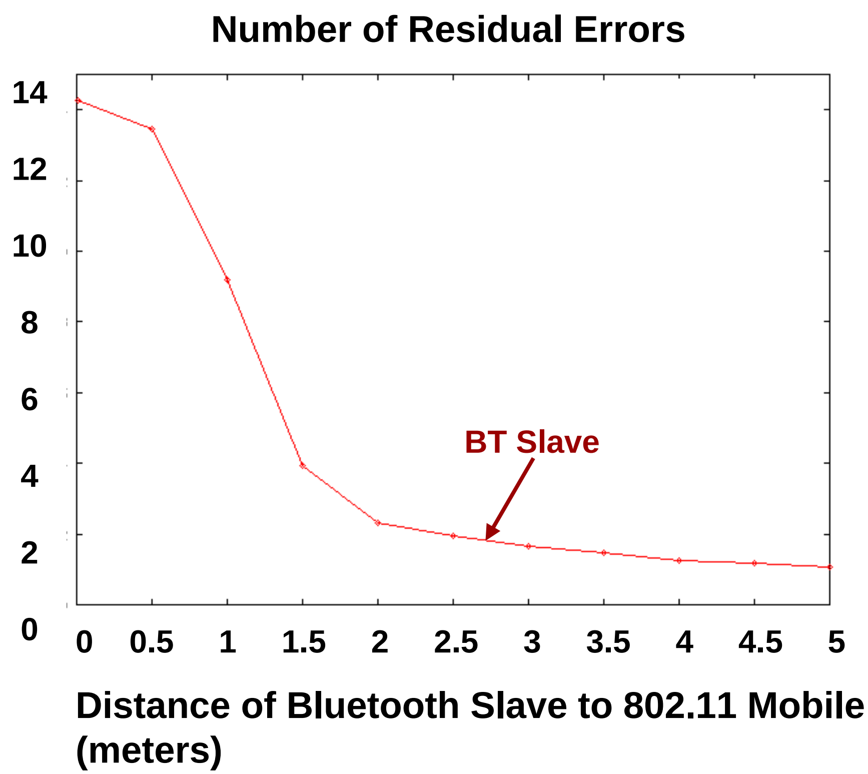




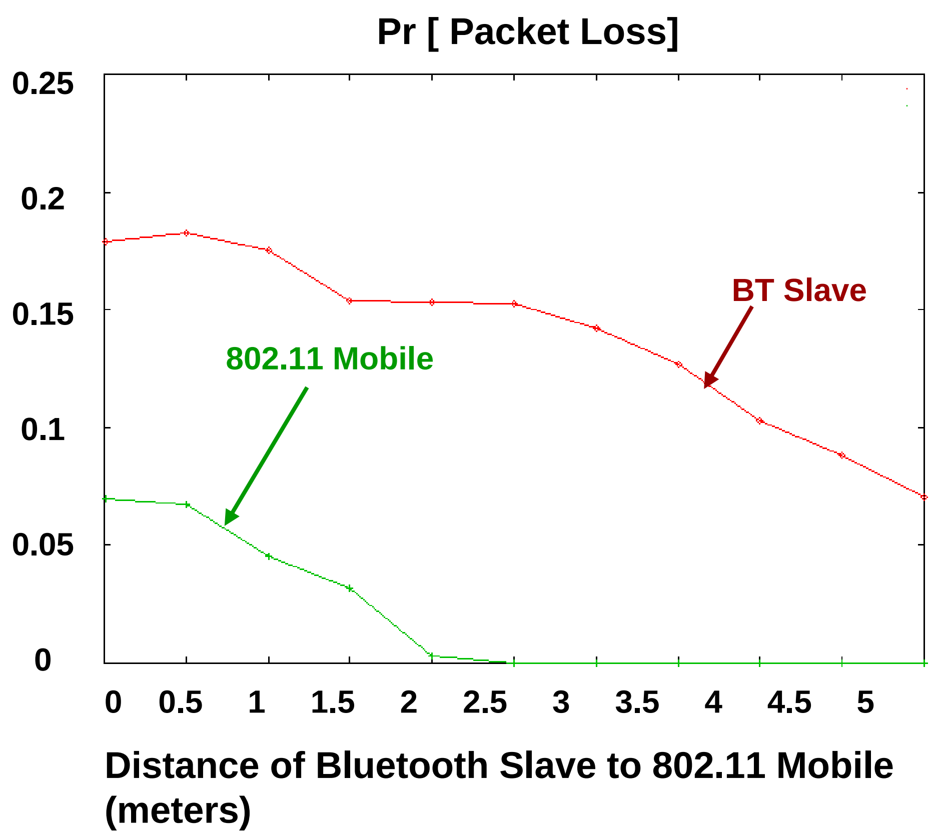


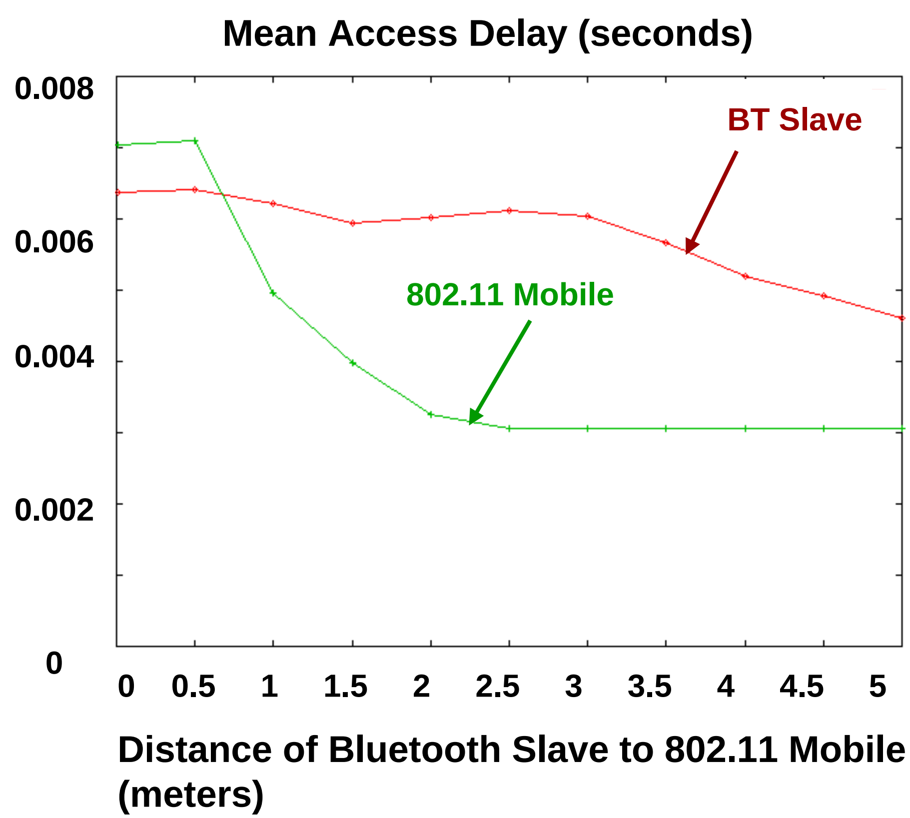
Experiment 1: Bluetooth voice packets with 802.11 interference



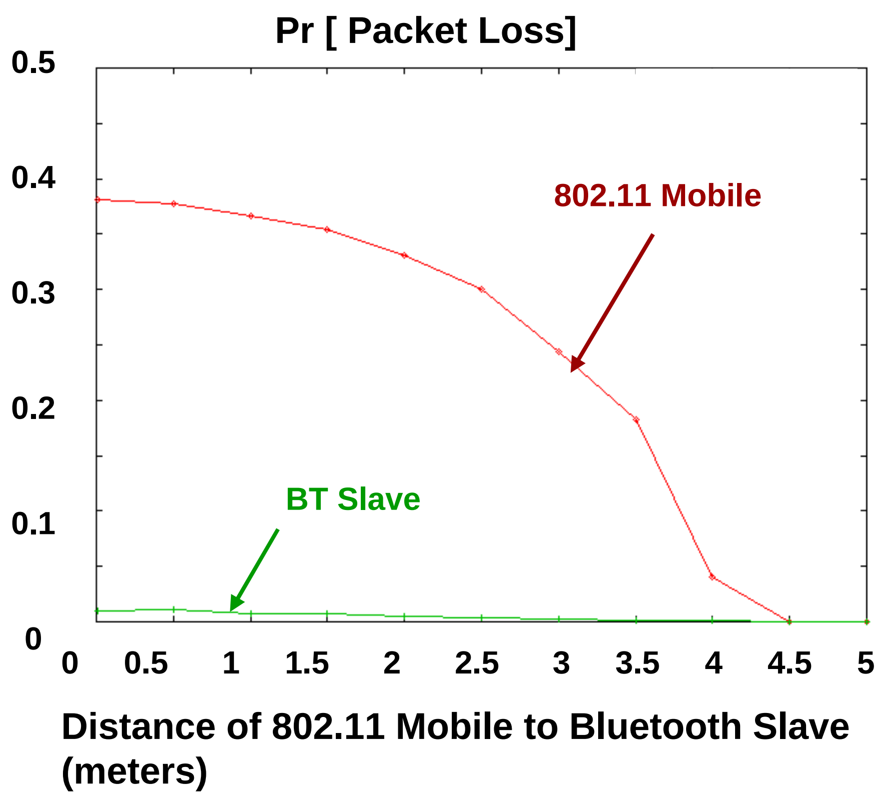


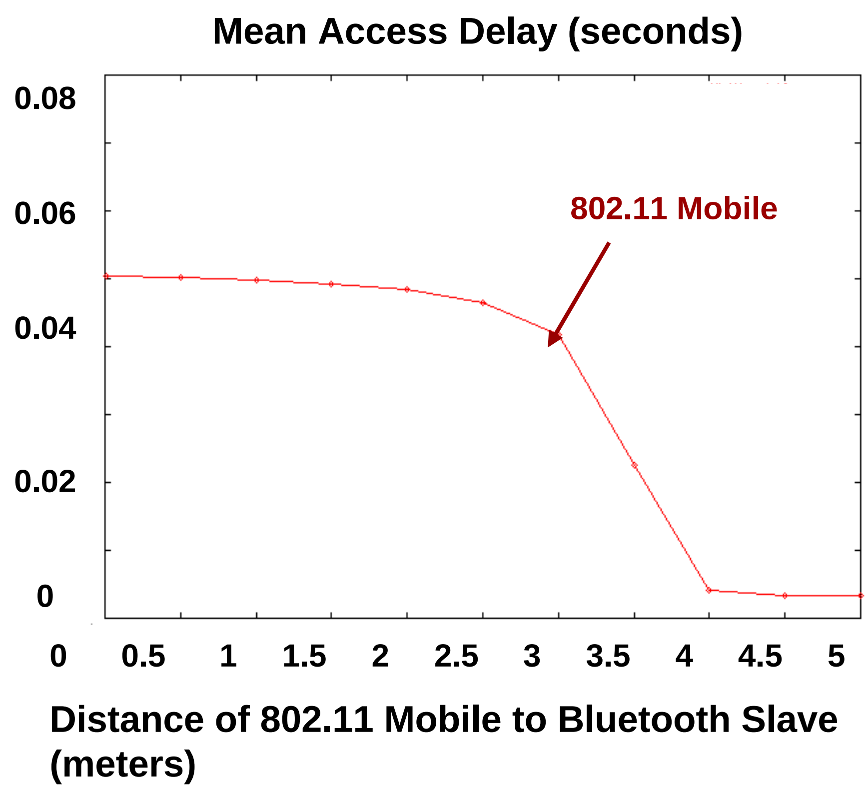
Experiment 2: Bluetooth data packets with 802.11 interference



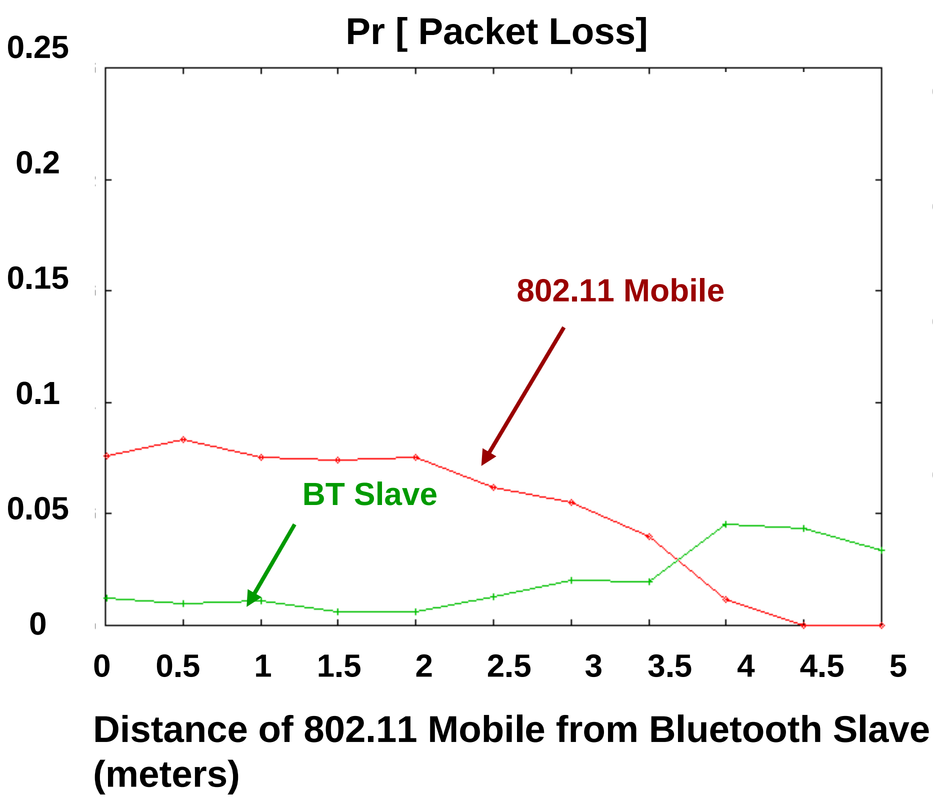


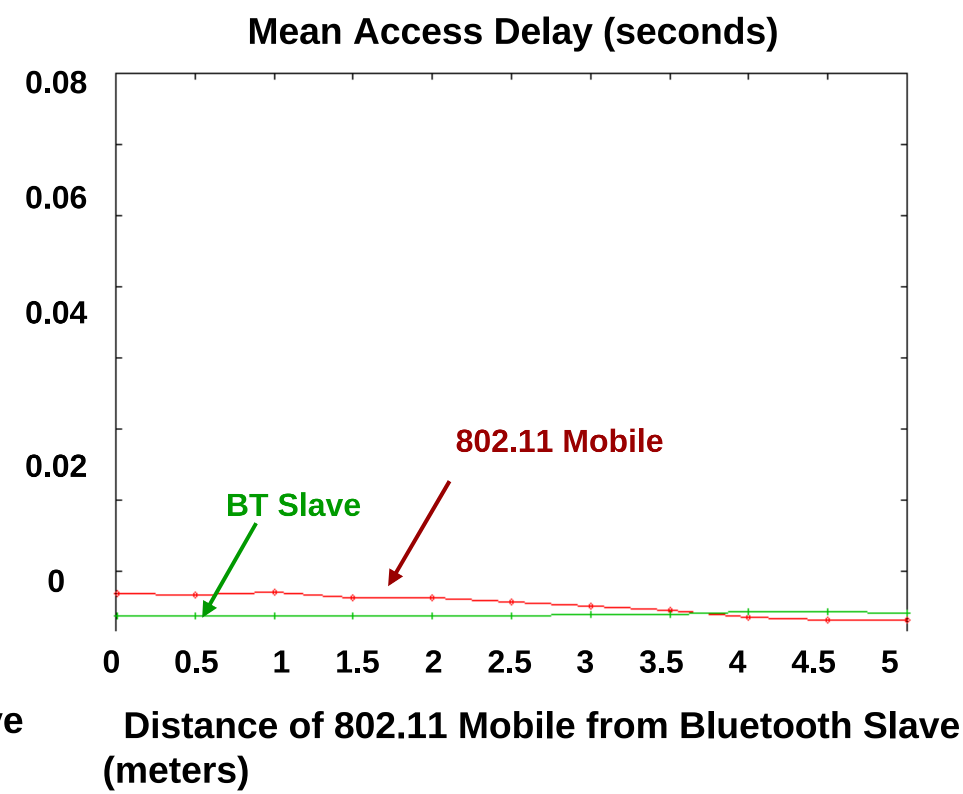
Experiment 3: 802.11 with Bluetooth voice as interference





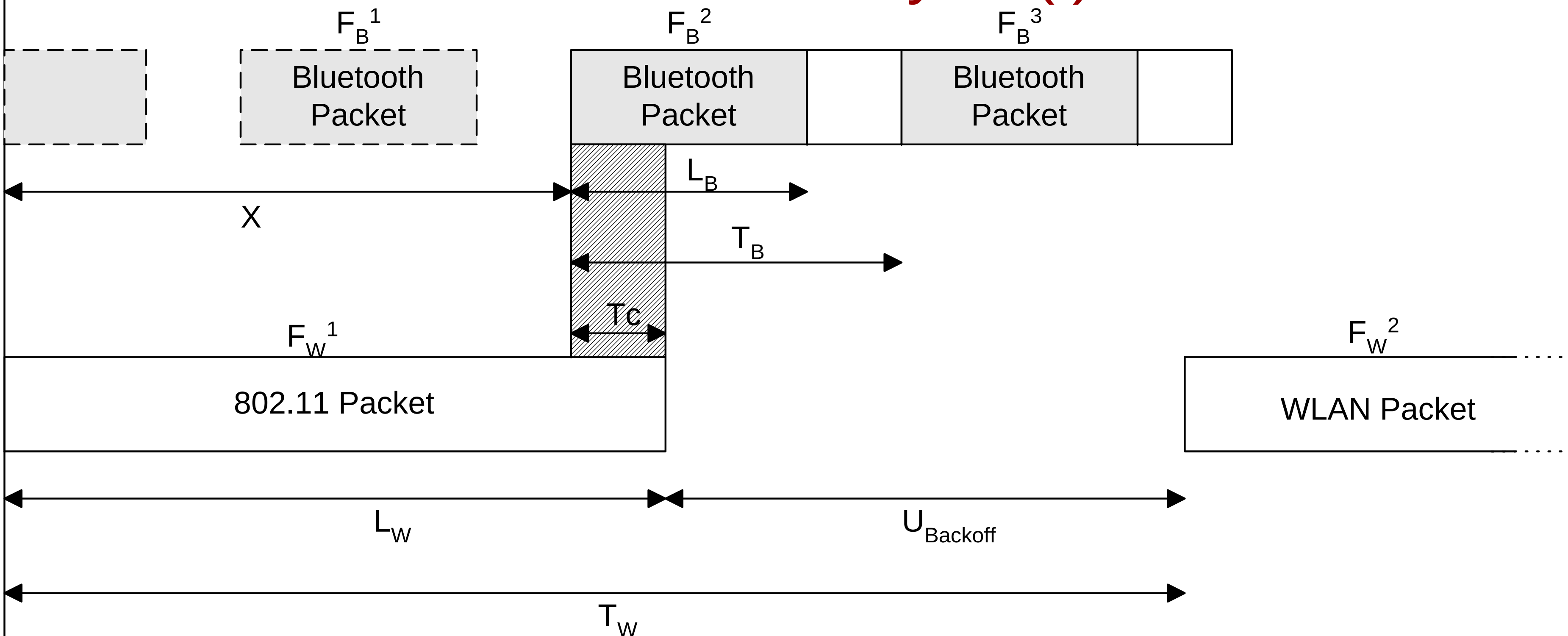
Experiment 4: 802.11 with Bluetooth data as interference





Analytical Modeling

Interference Analysis (I)



L_B/ L_W= length of Bluetooth / 802.11 packet

T_B/ T_W = interarrival time between two Bluetooth/ 802.11 packets

F_B/ F_W = frequency used by Bluetooth/ 802.11packet

T_C = collision time

X, F_B and F_W are independent and uniformly distributed random variables

$X \in 0..T_W$

$F_B, F_W \in 0..79$

Interference Analysis (II)

$$PE = \sum_{x=0}^{T_W} \sum_{f=1}^{79} Pr(\text{packet error} \mid X=x; F=f).p_x(x).\ p_f(f)$$

where

$$Pr(\text{packet error} \mid X = x; F = f) = 1 - (1 - BER)^{TC(x)}$$

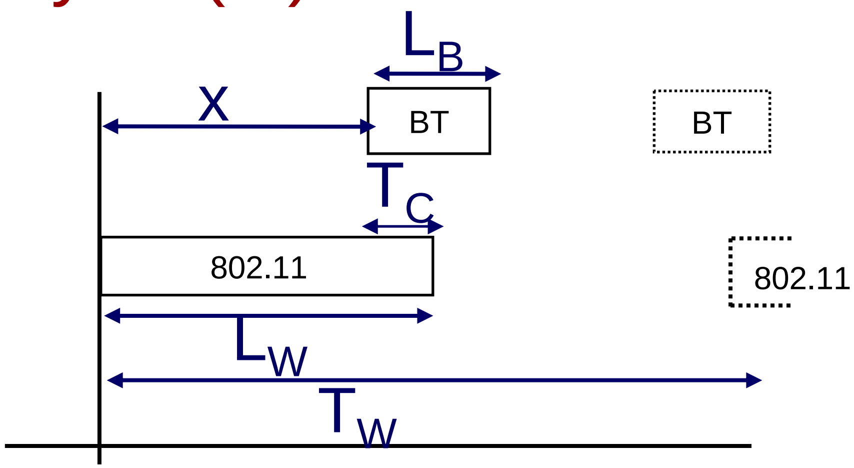
Therefore,

$$PE = (N/79)(1/T_W) \sum_{x=0}^{T_W} (1 - (1 - BER)^{TC(x)})$$

N = number of Bluetooth channels affected by 802.11 interference

Interference Analysis (III)

To compute T_C, there are 3 cases:



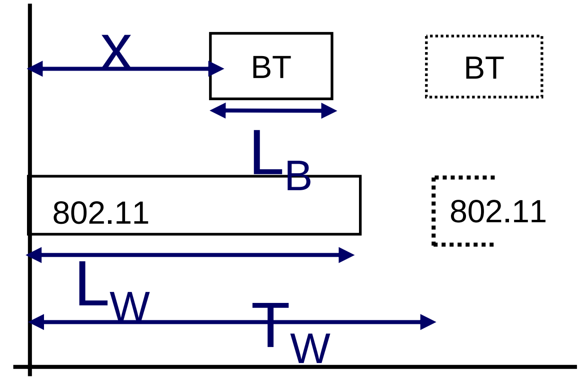
1) $L_B \le L_W$ and $L_B \le T_W - L_W$

$$
T_C(x) = \begin{cases} L_B & \text{if } x \le L_W - L_B \\ L_W - x & \text{if } L_W - L_B < x < L_W \\ 0 & \text{if } L_W \le x \le T_W - L_B \\ x + L_B - T_W & \text{if } T_W - L_B < x \le T_W \end{cases}
$$

2) $L_B \le L_W$ and $L_B > T_W - L_W$

3) $L_B > L_W$

Interference Analysis (IV)



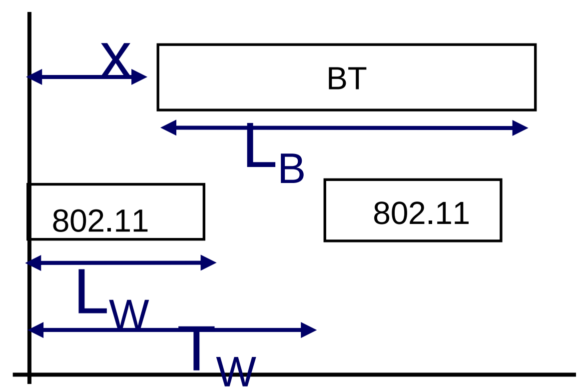
2) $L_B \le L_W$ and $L_B > T_W - L_W$

$$
\begin{aligned}
T_C &= L_B && \text{if } x < L_W - L_B \\
&= L_W - x && \text{if } L_W - L_B \le x < T_W - L_B \\
&= L_W + L_B - T_W && \text{if } T_W - L_B \le x \le L_W \\
&= x + L_B - T_W && \text{if } L_W < x \le T_W
\end{aligned}
$$

3) $L_B > L_W$

Define N(x) as the number of 802.11packets that hit a Bluetooth packet

$$
\begin{aligned}
N(X) &= \lceil L_B/T_W \rceil && \text{if } x \le T_W \lceil L_B/T_W \rceil - L_B \\
&= \lceil L_B/T_W \rceil + 1 && \text{otherwise}
\end{aligned}
$$



Interference Analysis (V)

Define T_i as the interval of time overlap with 802.11packet i

$$
\begin{aligned}
T_i &= \max(L_W - x, 0) && \text{if } i=0 \\
&= L_W && \text{if } i = 2, \ldots, N(x) - 1 \\
&= \min(x + L_B - (N(x) - 1)T_W, L_W) && \text{if } i = N(x)
\end{aligned}
$$

and

$$T_C = \sum_{i=1}^{N(x)} T_i$$

Analytical and Simulation Parameters Mapping (I)

1. Given the simulation parameters:
   - d = distance between transmitter and receiver
   - P_T = transmitted power
   - P_I = transmitted interference power
2. Compute Signal to Interference Ratio (SIR)
   - SIR = F(d, P_T, P_I)
3. Obtain BER and N from PHY layer simulation results
   - BER = F(SIR)
   - N = F(SIR)
4. PE = F(BER, N) (BER and N are used in the analysis)

Analytical and Simulation Parameters Mapping (II)

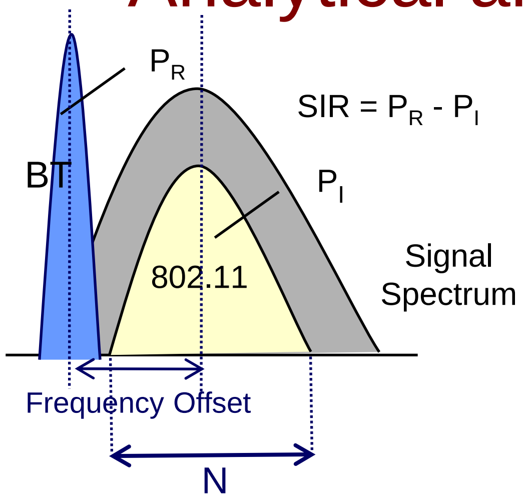
SIR is computed as follows:

$$L_p = \begin{cases} 32.45 + 20 \log (f.d) & d < 8 \text{ meters} \\ 58.3 + 33 \log (d/8) & \text{otherwise} \end{cases} \quad (1)$$

$$P_R = P_T - L_P \quad (2)$$

$$SIR = P_R - P_I \quad (3)$$

Analytical and Simulation Parameters Mapping (III)

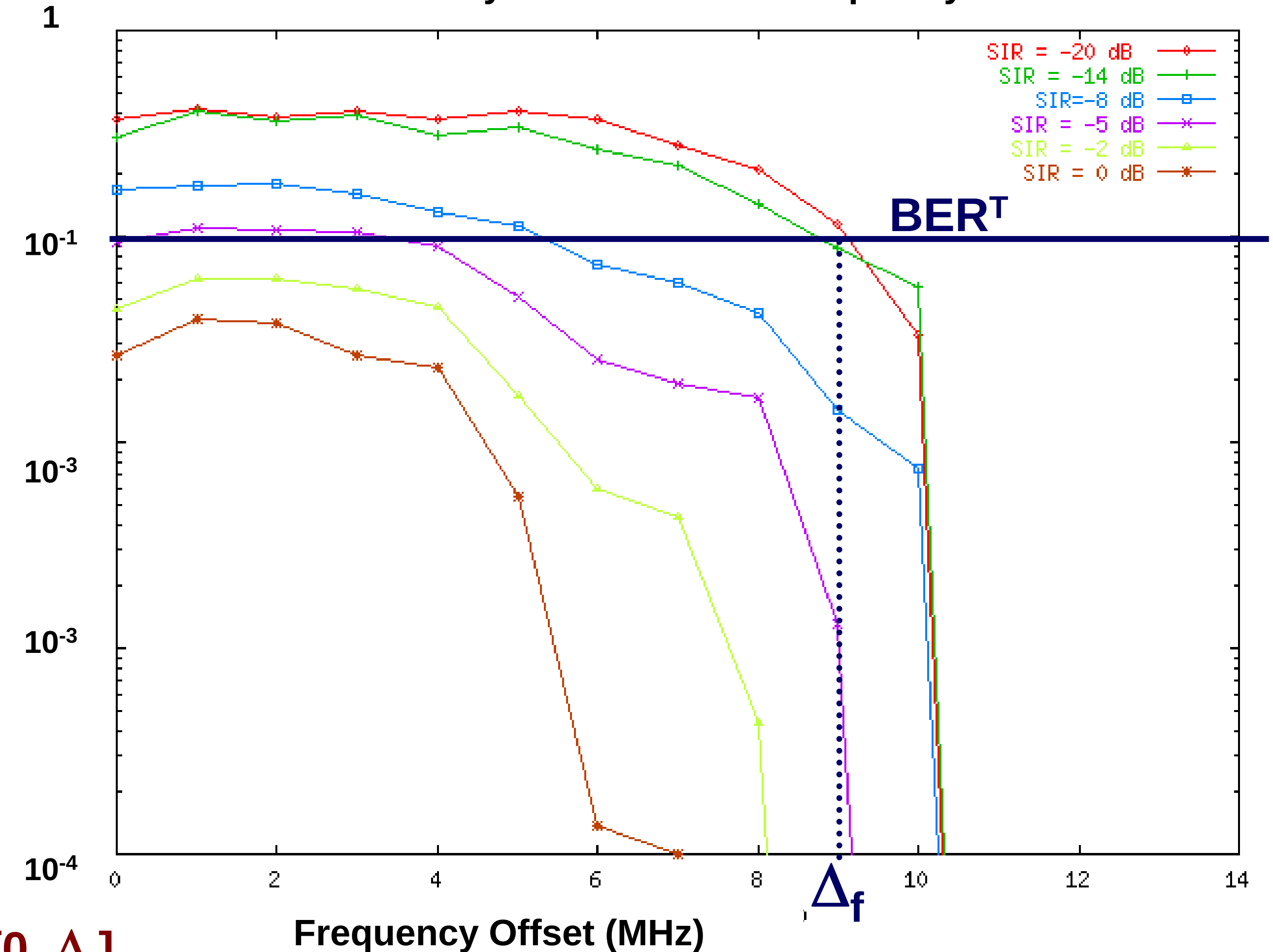


$N = 2 \times \Delta_f$

d (m)	SIR (dB)	N	BER
0.5	-20	18	3.68×10^{-1}
1	-14	16	3.41×10^{-1}
2	-7.95	16	1.37×10^{-1}
3	-4.43	16	7.6×10^{-2}
4	-1.93	14	4.2×10^{-2}
5	0	10	3.1×10^{-2}

$BER = \sum (BER_i)/\Delta_f \quad i \in [0, \Delta_f]$

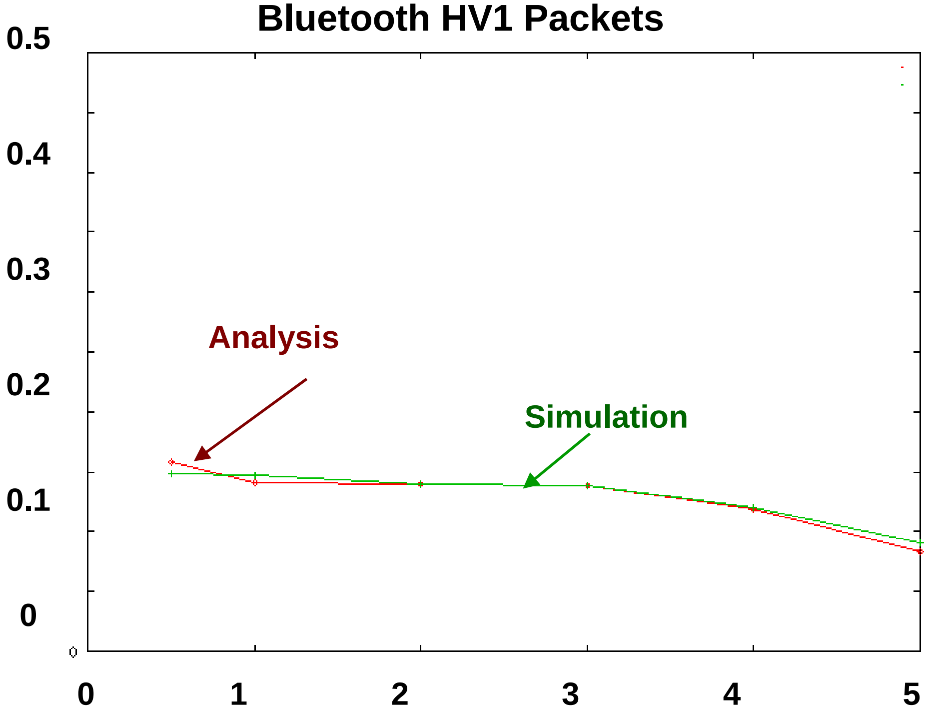
Probability of Bit Error vs. Frequency Offset



PHY Layer Simulation Results

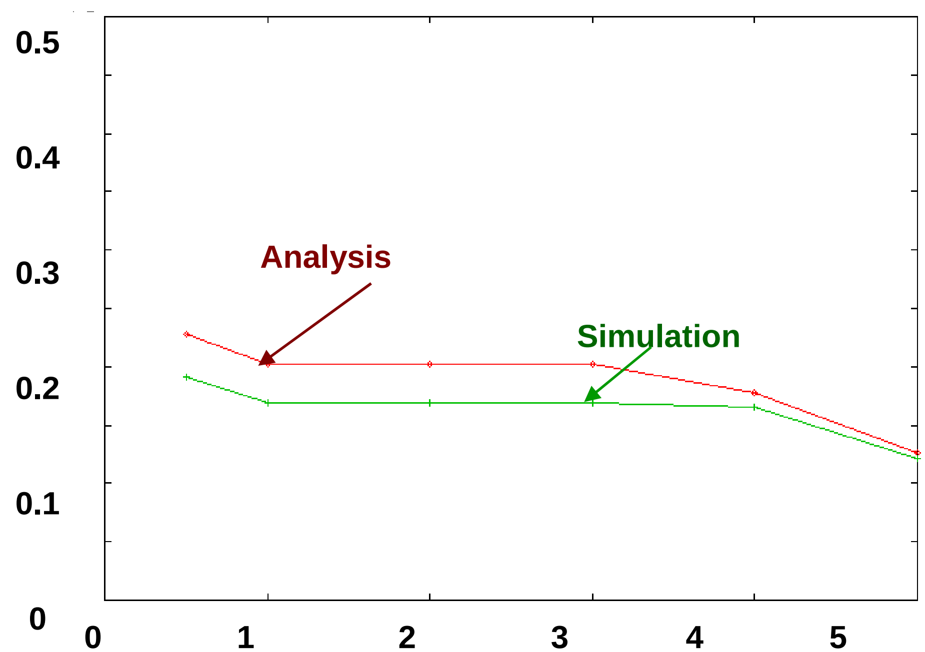
Analytical Results Validation

Pr [Packet Loss],
Bluetooth HV1 Packets



Distance of Bluetooth Slave from 802.11 Mobile (meters)

Pr [Packet Loss],
Bluetooth DM5 Packets

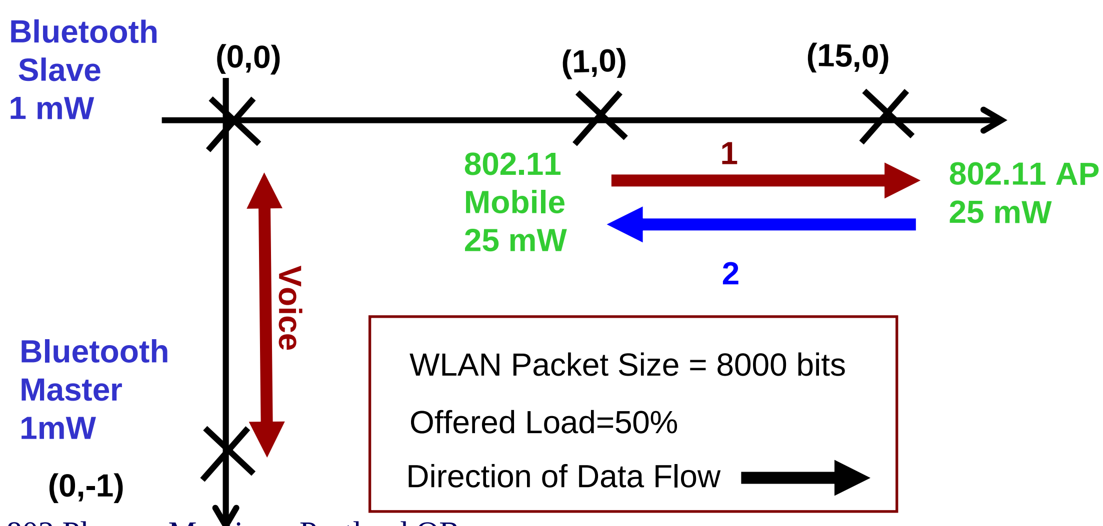


Distance of Bluetooth Slave from 802.11 Mobile (meters)

Experimental Validation

Experimentation, Analysis and Simulation: Comparative Results

		Analysis	Experimentation	Simulation
Techniques		Probability of packet error based on frequency and packet collision	2 Bluetooth Digianswer Development kit (Mark II)* and 2 Lucent Orinoco* Silver PCMCIA cards	MAC, PHY, Channel simulation models
BT Loss	1	12%	10%	12%
WLAN Loss	2	44%	37%	44%



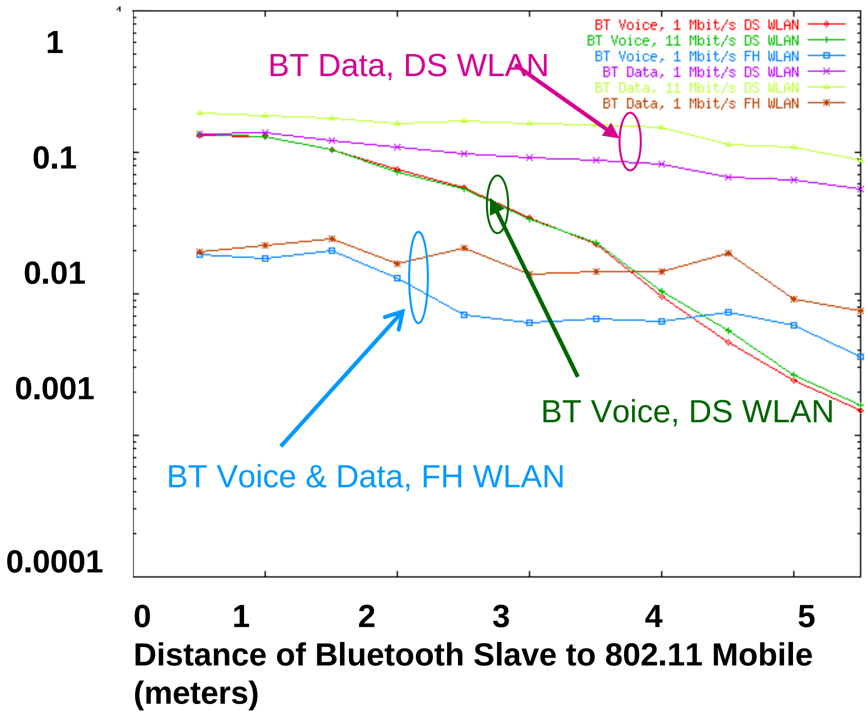
*Certain commercial equipment, instruments, or materials are identified on this page in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose

Performance Evaluation Cycle

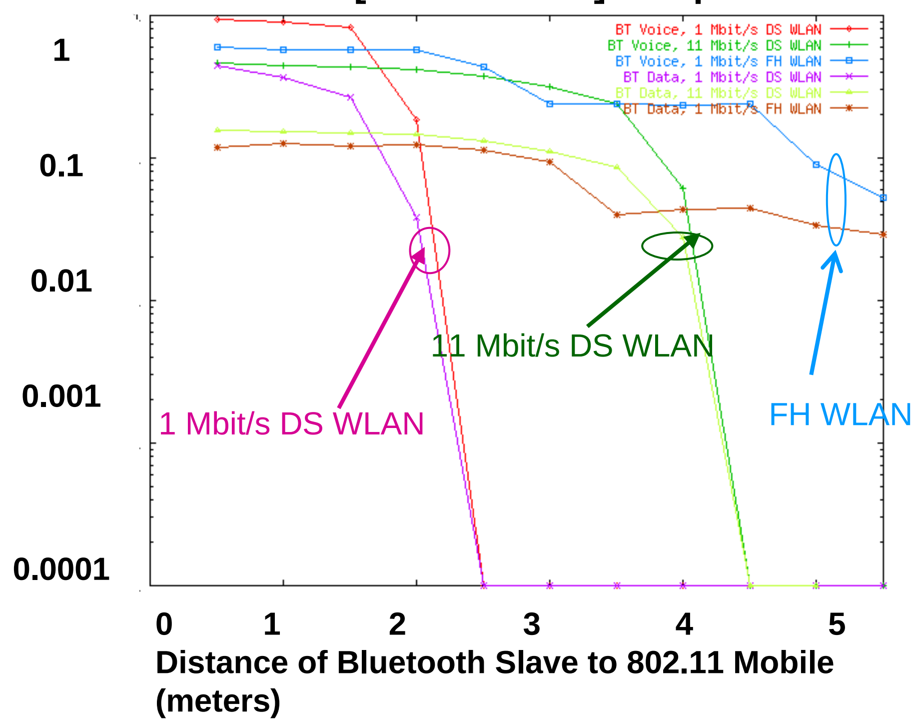
1. Controlled environment to identify parameters that may effect performance
   - Simple 4-node topology
   - On-off packet generation
   - Investigate parameters such as device type, modulation, transmission power, hop rate, offered load, traffic type, packet size
2. Realistic scenarios with higher layer protocol details
3. Large topologies with multiple interferers

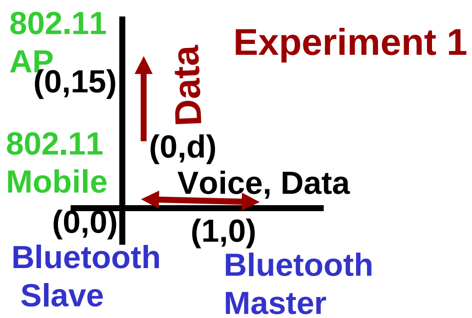
WLAN Device Type

BT Pr [Packet Loss] – Experiment 1

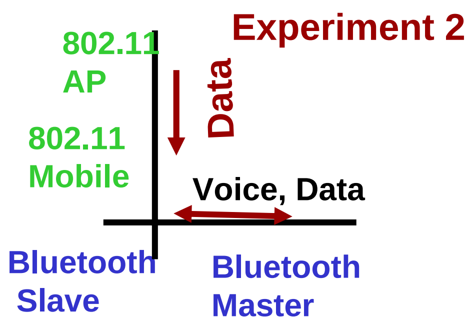


WLAN Pr [Packet Loss] – Experiment 2





BT Victim Signal



WLAN Victim Signal

Topology / Traffic	
BT Offered Load	**30%**
BT Tx Power	**1 mW**
Voice/Data	**HV1/DM5**
WLAN Packet Size	**8000 bits**
WLANs Tx Power	**25 mW**
WLAN Offered Load	**50%**
Traffic sources	**On-off**

Interference depends on the WLAN data rate and device type

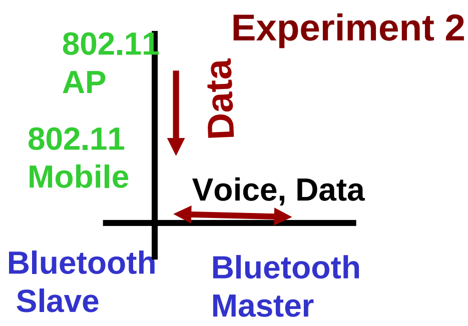
Bluetooth Transmission Power and Hop Rate

WLAN Probability of Packet Loss

BT Traffic	WLAN Offered Load 30%	WLAN Offered Load 60%
DM1	0.449	0.449
DM3	0.286	0.277
DM5	0.269	0.248

Probability of Packet Loss Versus BT Transmission Power

BT Traffic Type	BT Power (mW)	BT Loss Prob	WLAN Loss Prob.
Data –60%	1	0.2125	0.0961
	2.5	0.2085	0.1227
	10	0.1733	0.1358
Voice	1	0.1417	0.1253
	2.5	0.1179	0.1609
	10	0.0335	0.1977



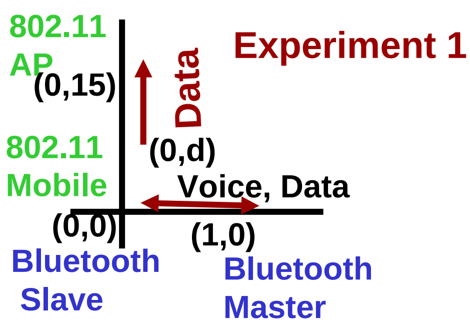
WLAN Victim Signal

Topology / Traffic	
BT Offered Load	**100%**
BT Tx Power	**1 mW**
Voice/Data	**HV1/DM5**
WLAN Packet Size	**8000 bits**
WLANs Tx Power	**25 mW**
WLAN Offered Load	**50%**
Traffic sources	**On-off**

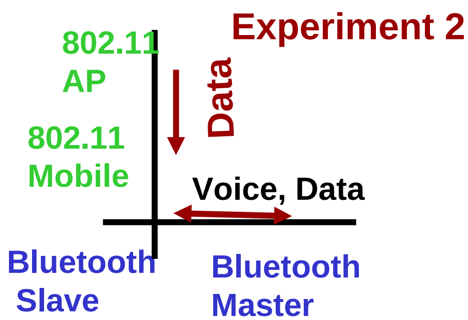
A higher transmission power and a higher Bluetooth hop rate causes more packet loss on the victim signal.

Other Factors Effecting Performance

- **WLAN Transmission Power** (Experiment 1)
  Increasing the 802.11 tx power between [1,5] mW triples the BT packet loss but does not affect the 802.11 results
- **Offered Load** (Experiment 1)
  The packet loss increases with the offered load
- **Bluetooth Traffic Type** (Experiment 2)
  Voice causes more interference than data traffic
- **Bluetooth Packet Size** (Experiment 1 & 2)
  A shorter packet size leads to less packet loss for Bluetooth but causes more interference on WLAN



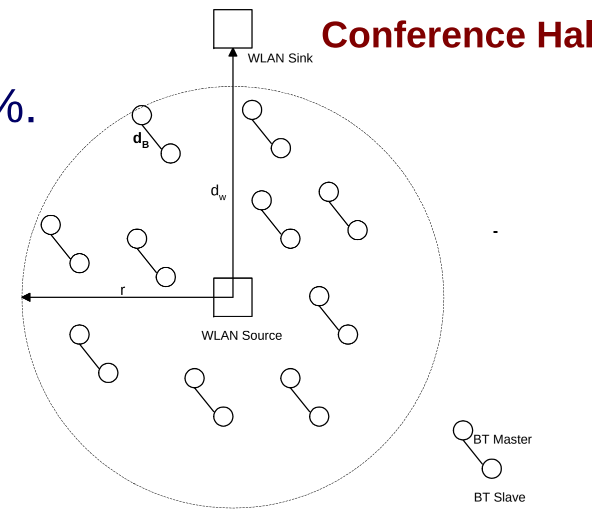
BT Victim Signal



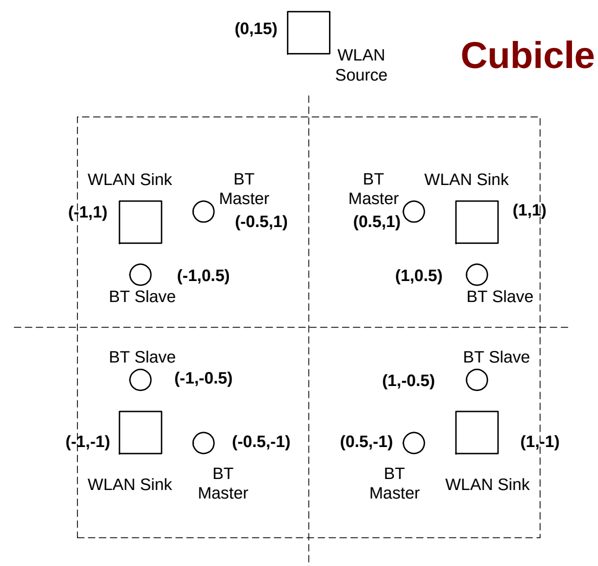
WLAN Victim Signal

Multiple Bluetooth Piconets

- **Bluetooth on Bluetooth interference**
  Packet loss due to other BT piconets is less than 1%.
- **Bluetooth on 802.11**
  10 BT piconets in 314.15 m^2
  100% of 802.11 loss with BT voice traffic,
  Up to 40% with BT data.



- **Bluetooth on 802.11**
  80% of 802.11 packet loss with BT voice
  57% with BT data .
- **802.11 on Bluetooth**
  0.7% of packet loss for BT data
  0.2% of packet loss for BT voice



Results exhibit strong dependence on the network topology, transmission power, & traffic distribution.

Parameter optimization is not a solution!

Few Observations on Performance

… on the effects of multi-protocol interference

Considered effects of parameters such as device type, transmitted power, offered load, hop rate, network topology on interference:

- A higher data rate WLAN is less prone to interference…: the packet loss for the WLAN 1 Mbit/s (45%) is about half the packet loss of the WLAN 11 Mbit/s (20%) with Bluetooth data interference
- …but causes more interference on Bluetooth: the packet loss for Bluetooth is 13% and 20% with the 1 Mbit/s and the 11 Mbit/s WLAN
- Shorter packet sizes are less prone to interference…: Higher Bluetooth hop rate (shorter packet sizes) is less effected by interference but causes more interference on WLAN
- Frequency hopping WLAN is less prone to interference: the packet loss is 40% and 90% for the WLAN 1 Mbit/s FH and DS, respectively
- Increasing the transmission power causes more interference on the victim device…: increasing the Bluetooth power from 1 to 10 mW leads to a 50% increase in the WLAN packet loss
- WLAN interference causes severe Zigbee performance degradation: up to 90% loss

Performance depends on protocol parameters and traffic used…

but parameter optimization may prove impossible!

Let’s develop solutions!!

Coexistence Components

1. Channel estimation
2. MAC layer protocol behavior
3. Channel selection
4. Modulation
5. Protocol collaboration

Channel Estimation

- Received Signal Strength Indication (RSSI)
  - Energy detection over a certain threshold
- Carrier Sense
  - Detection of a signal with specific characteristics
- Packet Error Rate
  - Rate of in-error packets to received packets
- Packet Acknowledgment
  - Unacknowledged packets or negative acknowledgement indication (when acknowledgments are expected) reflect the transmission quality in a channel.

MAC Layer Protocol Behavior

- TDMA solution for scheduling Bluetooth and 802.11 packets on the same device: one radio implementing both protocols
- Bluetooth packet size selection: traffic dependent, impractical with realistic applications
- Backoff and scheduling: select transmission time to avoid interference – no changes to chipset

Channel Selection

Channels may be *dynamically* selected based on the channel status

- IEEE 802.11b DSSS selects a center channel
- Zigbee dynamically selects a channel at initialization and during normal operation
- Bluetooth may reduce its hopping set in response to channel assessment information

Modulation

- Spread spectrum techniques
  - a transmission bandwidth that is several orders of magnitude greater than the minimum required signal bandwidth so that many users can simultaneously use the same bandwidth
  - Pseudorandom signal with noise-like properties
  - Inherent interference rejection capability
  - Elimination of narrowband interference
  - Resistance to multipath fading due to frequency diversity
  - Direct sequence spread spectrum multiplies baseband data by a pseudo-noise code generator
  - Frequency hopping spread spectrum involves a periodic change of transmission frequency
- Receiver Design
  - Coding
  - Notch filtering

Protocol (Non)/Collaboration

- Collaborative methods rely on communication between different protocols at a specific protocol layer in order to achieve coexistence
  - Protocols implemented on the same physical device can be collaborative
  - Multi-radio and “cognitive radio” technologies
- Non-collaborative methods do not use any form of communication between different protocols
  - Simply rely on channel estimation techniques

Let’s look at some examples

Example Solutions

1. Channel estimation – Dynamic channel estimation
2. MAC layer protocol behavior – Bluetooth scheduling
3. Channel selection – Bluetooth adaptive hopping
4. Modulation – WLAN rate scaling
5. Protocol collaboration – Non-collaborative

Open Issues and Recommendations

Related publications

- N. Golmie, N. Chevrollier, and O. Rebala, “Bluetooth and WLAN Coexistence: Challenges and Solutions,” IEEE Wireless Communications Magazine, Vol. 10, No. 6, December 2003.
- N. Golmie, “Bluetooth Dynamic Scheduling and Interference Mitigation,” in *ACM Mobile Networks*, MONET 2003, Vol. 9, No. 1, February 2004.
- N. Golmie, R. E. Van Dyck, A. Soltanian, A. Tonnerre, and O. Rebala, "Interference Evaluation of Bluetooth and IEEE 802.11b Systems," *ACM Wireless Networks* 2003, Vol. 9, pp. 202-211.
- N. Golmie, O. Rebala, "Bluetooth Adaptive Techniques to Mitigate Interference," Proceedings of IEEE GLOBECOM 2003, San Francisco, CA, December 2003.
- N. Golmie, N. Chevrollier, and O. Rebala, "Bluetooth Adaptive Frequency Hopping and Scheduling," *Proceedings of Military Communications*, MILCOM 2003, Boston, MA, October 2003.
- N. Golmie and O. Rebala, “Techniques to Improve the Performance of TCP in a mixed Bluetooth and WLAN Environment,” *Proceedings of the International Conference on Communications*, ICC, 2003.
- N. Golmie, “Performance Evaluation of a Bluetooth Channel Estimation Algorithm,” *Proceedings of the 13th IEEE Symposium on Personal, Indoor and Mobile Radio Communications*, Lisbon, Portugal, September 15-18, 2002.

More related publications

- N. Golmie, N. Chevrollier, and I. Elbakkouri, "Interference Aware Bluetooth Packet Scheduling," *Proceedings of IEEE Global Communications*, GLOBECOM'01, San Antonio, TX, N. 2001.
- N. Golmie, N. Chevrollier, "Techniques to Improve the Performance of Bluetooth in Interference Environments," *Proceedings of MILCOM* 2001, McLean, VA, October 2001.
- N. Golmie, R. E. Van Dyck, A. Soltanian, "Performance Evaluation of Bluetooth and IEEE 802.11 Devices Operating in the 2.4 GHz ISM Band," *Proceedings of the Fourth ACM International Workshop on Modeling, Analysis, and Simulation of Wireless and Mobile Systems*, MSWIM'01, Rome, Italy, July 2001.
- N. Golmie, F.Mouveaux, "Interference in the 2.4 GHz ISM Band: Impact on the Bluetooth Access Control Performance," *Proceedings of the 18th International Conference on Communications*, ICC'01, June 11-15, Helsinki, Finland.
- N. Golmie, "Interference in the 2.4 GHz Band," *Proceedings of the First International Conference on Applications and Services in Wireless Networks*, ASW'2001, Evry, France, Jully 25-27, 2001, pp.187-199.
- N. Golmie, F. Mouveaux, "Modeling and Simulation of MAC Protocols for Wireless Devices: Coexistence Performance Evaluation," *Proceedings of OPNETWORK* 2000, Washington DC, August 28-September 1, 2000.

Other publications related to this topic

- Howitt, “WLAN and WPAN coexistence in UL band ," IEEE Transactions on Vehicular Technology", Vol. 50, No. 4, July 2001, pp. 1114-1124.
- J.D. Laster, and J.H. Reed, "Interference Rejection in Digital Wireless Communications", IEEE Signal Processing Magazine, May 1997, pp. 37-62.
- C. F. Chiasserini, and R. R. Rao,"Coexistence mechanisms for interference mitigation between IEEE 802.11 WLANs and Bluetooth", Proceedings of INFOCOM 2002", pp. 590-598.
- IEEE Std. 802-15-2, “Information technology Telecommunications and information exchange between systems Local and metropolitan area networks Specific requirements Part 15.2: Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands,” June 2003.
- J. Lansford, A. Stephens, and R. Nevo, "Wi-Fi (802.11b) and Bluetooth: Enabling Coexistence", IEEE Network Magazine, Sept/Oct. 2001, Vol. 15, No. 5, pp. 20-27.
- Federal Communications Commission, “Title 47, Code for Federal Regulations, Part 15", October 1998.
- B. Sklar, *Digital Communications: Fundamentals and Applications*, Prentice Hall, 1997.
- T. Rappaport, *Wireless Communications, Principles and Practices*, Prentice Hall, 1996.
- Bluetooth Special Interest Group, “Specifications of the Bluetooth System, vol. 1, v.1.0B 'Core' and vol. 2 v1.0B 'Profiles'", Bluetooth Special Interest Group,December 1999.
- IEEE Std. 802-11, “ IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification”, June 1997.

IEEE 802.15 Contributions

- N. Golmie, “MAC Scheduling Mechanisms,” IEEE 802.15/02-036r2, Dallas, TX, January 2002.
- N. Golmie, “MAC Scheduling Mechanisms,” IEEE 802.15/01-316r1, Portland OR, July 2001.
- N. Golmie, “MACModeling and Simulation Results ,” IEEE 802.15/01-317r1, Portland OR, July 2001.
- N. Golmie, “Coexistence Modeling Overview,” IEEE 802.15/01-318r1, Portland OR, July 2001.
- N. Golmie, “Interference Aware Bluetooth Scheduling Techniques,” IEEE 802.15/01-143r0, Hitlon Head, NC, March 2001.
- N. Golmie, R. E. Van Dyck, A. Soltanian, “Bluetooth and 802.11b Interference: Simulation Model and System Results,” IEEE 802.15/01-195r0, April 2001.
- N. Golmie, "Bluetooth Interference with 802.11 DS: MAC Simulation Results, " IEEE 802.15/01-077r0, January 2001, Monterey, CA.
- N. Golmie and N. Chevrollier, "Power Control and Packet Scheduling for Bluetooth to Avoid 802.11 Direct Sequence Interference, " IEEE 802.15/01-063r0, January 2001, Monterey, CA.
- N. Golmie, "Using a Combined MAC and PHY Simulation Model to Measure WLAN Interference on Bluetooth, " IEEE 802.15/00-388r0, November 2000, Tampa, FL.
- N. Golmie, "Impact of Interference on the Bluetooth Access Control Performance: Preliminary Results,"IEEE 802.15/00-322r0, September 2000, Scottsdale, AZ.
- N. Golmie, "First Test Scenario: MAC Simulation Parameters and Performance Measurements, " IEEE 802.15 Standard Group, IEEE 802.15/00-222r0, May 2000, Seattle,WA
- N. Golmie, "Update on the MAC Coexistence Modeling Effort," IEEE 802.15 Standard Group, IEEE 802.15/00-134r0, May 2000, Seattle, WA.
- N. Golmie, "Performance Metrics of MAC Coexistence Evaluation," IEEE 802.15 Standard Group, IEEE 802.15/00-103r0, May 2000, Seattle WA.
- N. Golmie, F. Mouveaux, " WPAN Coexistence Performance Evaluation: MAC Simulation Environment and Preliminary Results," IEEE 802.15 Standard Group, IEEE 802.15/00-66r0, March 2000, Albuquerque, NM.
- N. Golmie, "MAC Performance Evaluation in Coexistence Environment," IEEE 802.15 Standard Group, IEEE 802.15/99-117r1, Kawai, HI.

Final Slide

Thank you!