S-72333 PhD Seminar on Radio Communications

Coexistence and Interference of WLAN (IEEE 802.11b) and Bluetooth WPAN

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WLAN / WPAN coexistence in the 2.4-GHz ISM band

IEEE 802.11b (DSSS) and Bluetooth (FHSS) operate at 2.4GHz ISM

- Two different wireless systems co-located in same unlicensed frequency band in the nearby generate mutual interference that impacts on the system performances.

→ **Coexistence: the closest the worst**

• Some expected results: PER might increase significantly, WLAN throughput might drop significantly, Bluetooth voice link worst than data link because no packet retransmission?…

•Coexistence = study of potential mutual interference of systems that should not prevent from proper operations evaluated by:

- Extensive mathematical model of mutual interference between 802.11b and Bluetooth by IEEE 802.15.2 Coexistence Task Group.
- Different mathematical models of mutual interference.
- Empirical results from certain experimental setups.

Overview of radio 802.11b interface

IEEE 802.11b DSSS technology, DRs =1, 2, 5.5, 11 Mbps

- Spreading to combact inband interference smuts the interfering signal over the whole channel bandwidth → however it does not prevent from error if BT in the vicinity!

- 79 MHz frequency band divided into 3 channels spanning channel bandwidth = 22MHz

- DR produced by varying modulation & channel coding:
  - 1Mbps: DBPSK modulation, every transmitted bit encoded into a 11-chip Barker symbol. Chips transmitted at 11Mchips/s.
  - 2Mbps: DQPSK modulation, pair of transmitted bit encoded into two 11-chip symbols, generated by Barker code. Chips transmitted at 11Mchips/s.
  - 5.5 (11) Mbps: CKK modulation, every 4 (8) transmitted bits are encoded into 8-chip symbol. Each symbol generated by a Walsh code. Chips transmitted at 11Mchips/s.

Overview of Bluetooth radio interface

- FHSS at transmission rate = 1Mbps over short distances: 79 RF channels displaced by 1MHz, fast new frequency hop (1600 hops/s), short packet, FEC.
- Slots in TDD channel are allocated by the master and used for master/slave transmission alternately.

Bluetooth network piconet composes by a master device and slave devices (from 2 to 6) connected via Bluetooth in ad hoc network.
The occupation of FH/TDD channel slot intervals by users done according to a pattern that depends whether Bluetooth voice link or data link is transmitted.

Single Packet

Ack

Packet Slot length

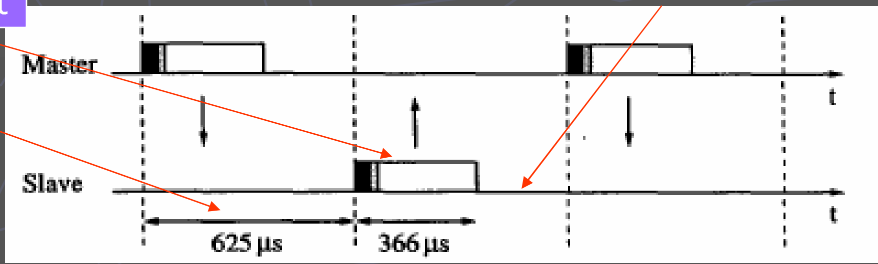
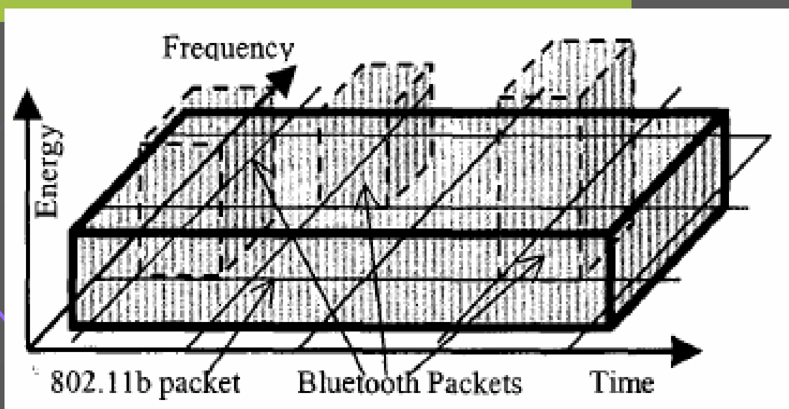


Fig. FH/TDD channel in Bluetooth: each time slot corresponds to a RF channel.

Collision scenario



Collision occurs when a BT packet hops on the DSSS band in frequency and overlaps in time

When do BT and 802.11 produce harmful interference to each other?
We focus on the reliability / degradation of performance of the 802.11 in the presence of interference from BT radios.

Model Assumptions

Necessary assumptions on:
1. WLAN Network topology
2. User density / user positions for both systems
3. Propagation model / environment / scenarios
4. Network traffic load for 802.11 and BT (piconet).

Usually the interefernce has been investigated and proposed for:
1. Infrastructure topology
2. No higher density environment analyzed: only system with AP, WLAN STA, BT STA.
3. A simplified PL
4. Constant traffic for BT, typical utilization model not considered.

Parameters to define are:
1. Distances between WLAN STAs, APs,
2. density of WLAN STA,
3. Transmit power for both WLAN STA and AP: +20dBm
4. BT transmit power: 0dBm
5. # BT piconets co-located at each node

Zyren (qualitative) Model, [5]

1. WLAN STAs located 20m far from AP.
2. Density: 1 WLAN STA every 25 m2
3. Transmit power WLAN= +20dBm
4. BT piconet: transmit power BT= +0dBm

- The interference suscettivity of the 802.11 depends on desired signal from AP: an 11Mbps DSSS radio can provide reliable services when a narrowband interferer as BT falls within its pass band if the SIR is greater than roughly 10dB! (Conservative, tested in lab!)

1. Packet size=750B.
2. A fully loaded BT interferer

- When BT interferer > 10dB SIR threshold: dropped packets due to overlap in time and frequency. Number of potential interferes a STA is exposed depends on the range from the AP: suscettivity of WLAN to BT increases as a function of the range of distance AP-STA
- There is only 25% probability that an active BT transmitter will hop in a DSSS band. Even less if consider packet length. But we should take into account collision also with ack!
- Throughput drops from 7.5Mbits to 3.5Mbits
- Based on typical BT utilization: 802.11 shows good reliability in a fairly high dense environment.

Modeling mutual interference of IEEE802.11b & Bluetooth WPAN

Mathematical model of mutual interference by IEEE 802.15.2 Coexistence Task Group.

- In the OSI model IEEE 802 develops standards for L1 (PHY) & L2 (Data link).

- Design of PHY (RF layer in Bluetooth) & MAC, Logical Link Control (Baseband and Link Manager in Bluetooth) has major impact on the performance of wireless network in presence of interference.

For model details [7]:

PHY layer model for Bluetooth: Bluetooth RF layer. Model + TX GFSK modulator at 1Mbps + RX: baseband filter at DR=1Mbps + GFSK demodulator + detector

PHY layer model for 802.11 similarly…

Results from the math model

- By using PHY models of 802.11 & Bluetooth the model calculates the BER of the two systems working simultaneously. **BER(802.11-Bluetooth interferer).** Curves for each of 4 DRs.

-To calculate BER for different application scenarios, SIR needed at various RXs.

- SIR depends on transmit powers on BT and WLAN node, distances (TX-RX), path loss of RF signal.
- PL formula
- Given a geometric distribution of WLAN and WPAN nodes, the SIR is calculated at various receivers.
- PHY models calculated BER for both systems for the time intervals of overlapping transmissions. This info is used by MAC in order to calculate some metrics (PER, throughput, NT latency) and det packet error and retransmission.

- MAC simulation: not accurately!

Results from the math model 3

Calculation of PER of 802.11b at 1Mbps and at 11Mbps in the presence of a BT interferer

- BT traffic: voice
- d (WLAN TX/RX) = 15m

Results:

- At 1Mbps PER ~ 65% → throughput = 35%

As the SIR increases BER drops sharply because of spreading

- At 11Mbps PER ~ 30% because the duration of the packet is shorter at higher DR: the probability of collision drops as the time duration of transmission decreases even though 11Mbps does not benefit from processing gain.

Observations and limitation of the model

- Dropping WLAN DR not always ok because at lower DR packet longer in duration and PER might increase.
- Beyond certain distance processing gain at 1Mbps does not reduce PER.
- Assumptions, no account for situation of close proximity.
- Coarse assumptions, no system dynamics
- No detail or not considered WLAN PHY:
  - different DRs,
  - channel coding schemes,
  - relative power between BT & WLAN
  - Signal propagation characteristics, no inpact of time-space varying channel
- No detail MAC

Degradation for multiple 802.11b STAs due to BT

- Degradation depends on scenarios, devices positions, NT topologies.

- Models based on SIR requirements for 802.11 and Bluetooth receivers.

NT topologies for WLAN system within a BSS in presence of Bluetooth radio system at 2.4GHz:

-Point-to-point (an AP, a WLAN station,STA): well investigated (tolerable interference levels)

-Multiple STA, an AP: more realistic! Also MAC – Access methods described.

- The model considers a SCENARIO that comprises: multiple STAs, an AP, uncoordinated BT radio interferers
- It estimates throughput of IEEE 802.11b as function of WLAN and Bluetooth parameters

WLAN and Bluetooth parameters

The model [1] includes:

- 802.11b MAC modeling
- P(time coincidence)
- P(frequency coincidence)
- P(collision)
- Numerical results

NETWORK PARAMETERS: IEEE 802.11(B) AND BLUETOOTH

Parameters	Values
Probability of hidden station	0.08 or 0.16
Capture parameter	1.5
Propagation delay	1[μsec]
WLAN data rate	2, 11[Mbps]
Bluetooth data rate	1[Mbps]
Slot duration	20[μsec]]
PHY header	128[bit]
MAC header	272[bit]
ACK	112[bit]
CTS	160[bit]
RTS	160[bit]
SIFS	10[μsec]
DIFS	50[μsec]
WLAN EIRP	20[dBm]
BT EIRP	0[dBm]
Noise floor	-95[dBm]
Max # of wall between STAs	3
Max # of wall between BT devices	0
Max distance between STAs	60√2[m]
Max distance between BT devices	10[m]
Loss per wall	15[dB]

System Throughput

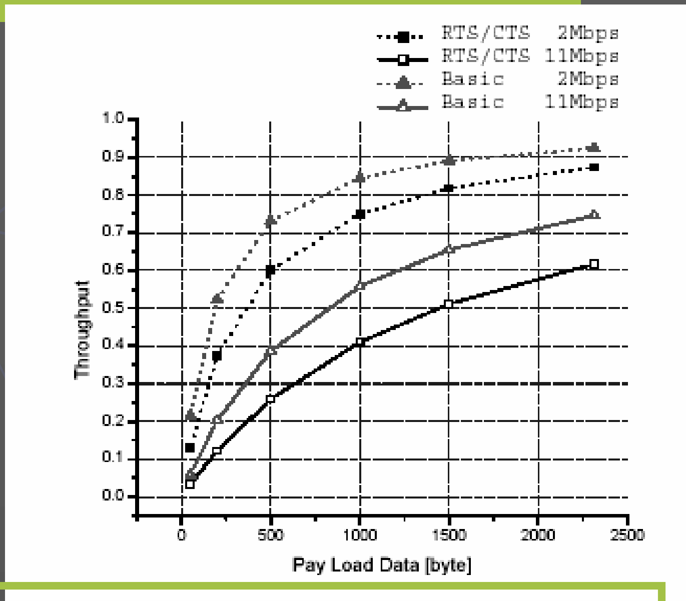


Fig. . Theoretical maximum throughput (normalized to its raw data rate) of IEEE 802.11b systems for basic access method and RTS/CTS access method.

Time coincidence analysis

-BT frame duration T_{BT}=625 µs, txm time t_{BT}= 366 µs

-802.11b frame duration T_P=1210 µs (PHY&MAC header for 1500B packet at 11Mbps)

-HP: Start txm for BT hop times as uniform r.v.

-#BT slot time overlapping in time with 802.11b is n or n-1

Overlapping n BT slots:

P_{n-1}= [T_{BT} *(n-1)-T_{BT} –t_{BT}-FD]/ T_{BT}

P_n =1- P_{n-1}

FD=802.11 frame duration (payload + headers)

→ n_{MAX}=3

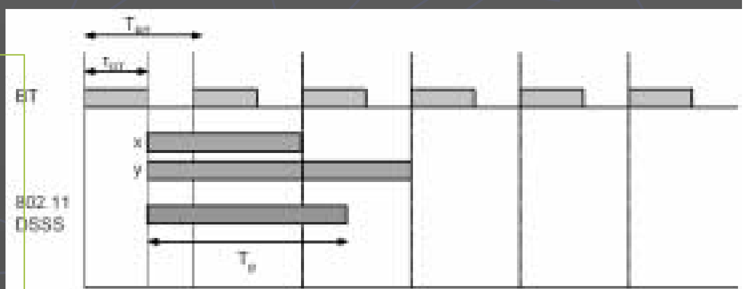


Fig. Time coincidence between a BT piconet slot and a IEEE 802.11b packet. For example, if x < Tp < y, then the IEEE 802.11b packet could collide with 2 or 3 BT slots.

Collision analysis

- Frequency coincidence occurs when the transmit frequencies of a BT piconet result in a packet error.

-If a nearby piconet active there is still probability that 802.11 STA receives succesfully a packet.

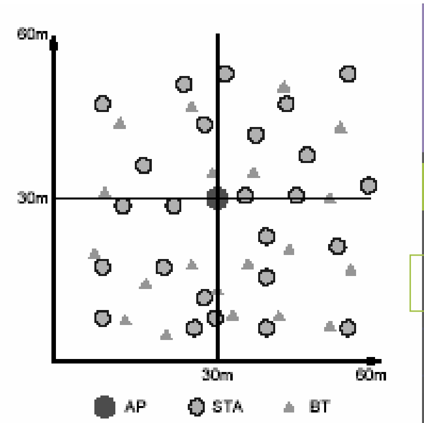
-Packet is destroyed if both overlap in time and frequency occurs.

-Collision with n slot overlap: $P_{coll}(n) = 1- (1- (P_{hop}*L_{BT}))^n$

-L_{BT} = piconet load factor

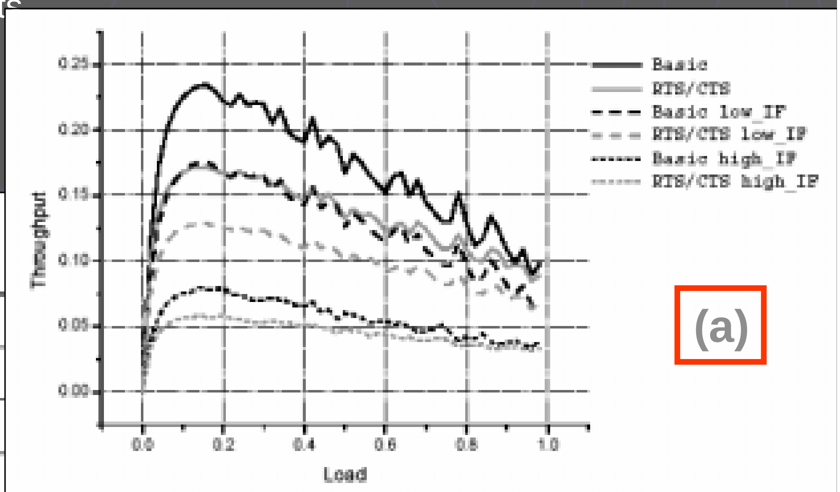
-Overall collision: $P_{tot}(n) = (P_{n-1} * P_{coll}(n)) - (P_n * P_{coll}(n))$

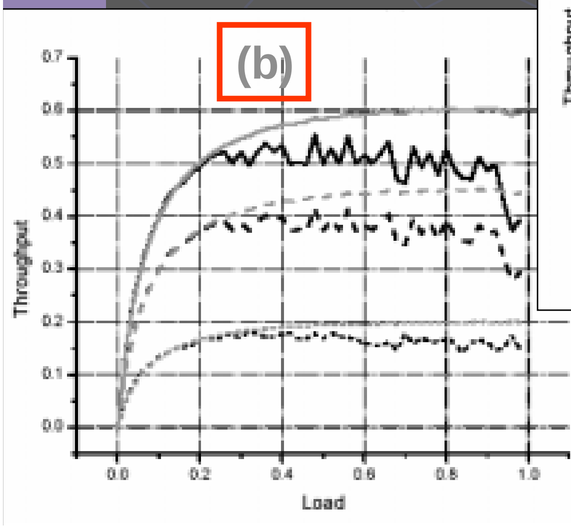
-**Collision from m BT piconets:** $P_{mult}(m) = 1- (1- P_{tot}(n))^m$



Numerical results

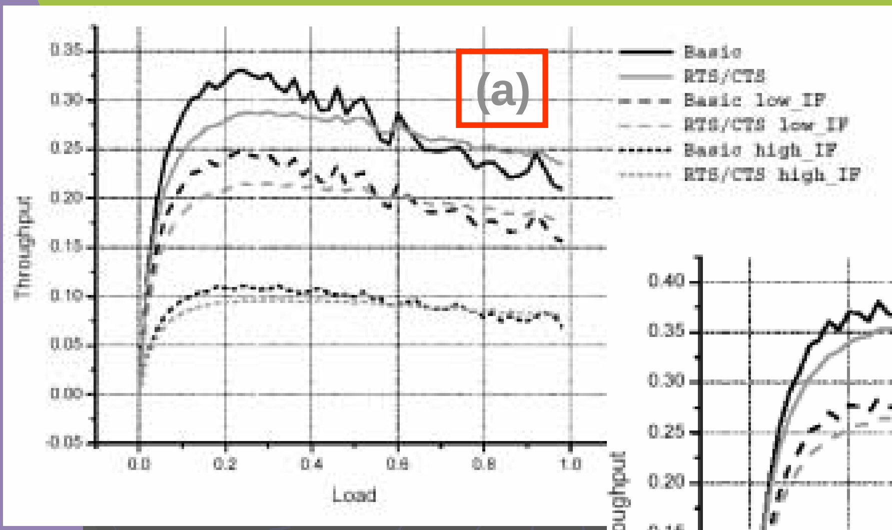
Distribution of AP, STAs, and BT piconets



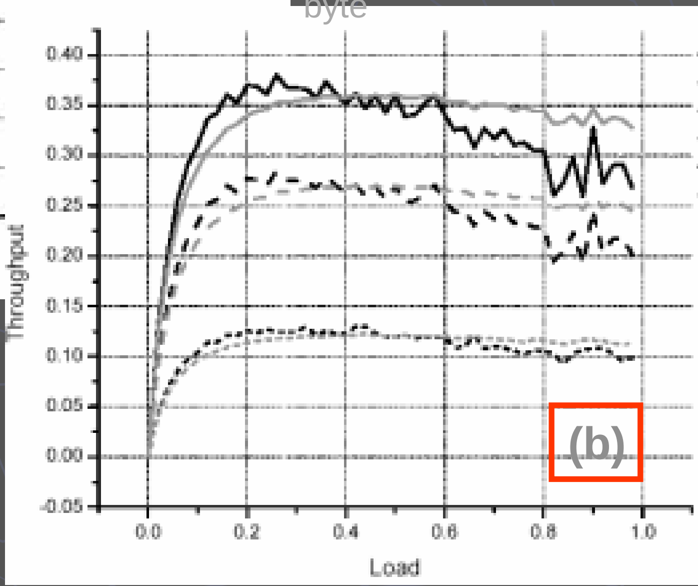


IEEE 802.11 WLAN data rate of 2Mbps. Ph = 0.08 (a) payload size of 100 byte and (b) payload size of 1500 byte
Ph= Probability of hidden terminal

Numerical results



IEEE 802.11 WLAN data rate of 11Mbps. Ph = 0.16
(a) payload size of 100 byte
(b) payload size of 1500 byte



Throughput degradation of WLAN STAs of 25% and 66% at respectively 2Mbps and 11Mbps

Interference in a office environment

- Typically analysis of interference without respect with typical office environment.
- Testbed for pratical tests:
  - 20dBm DSSS Lucent Orinoco 802.11b 11Mbps PC cards,
  - 20dBm BT Diaswear Development Module PC card (Demo Cards)

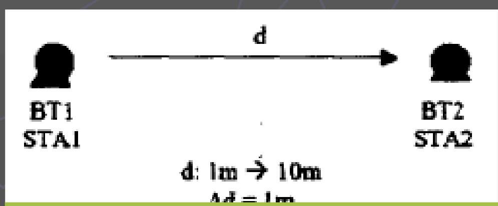
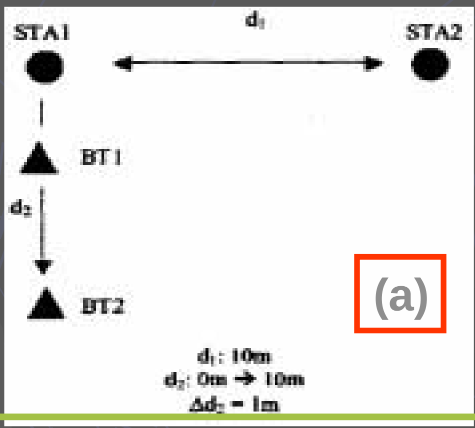


Fig. Ad hoc radio application

Scenarios: open office in ad-hoc NT

- 6 scenarios investigated for interference
- STA→802.11,
- BT → Bluetooth. Voice&data separated scenarios



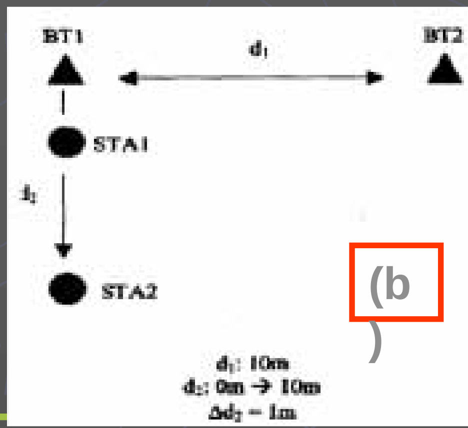


Fig. Effects of BT interferer on 802.11b (a) and of 802.11b interferer on Bluetooth (b). STA2 & BT2 far enough: no intereference. Both cards operating on the same PC (adjacent on each other).

Open office in ad hoc NT: results

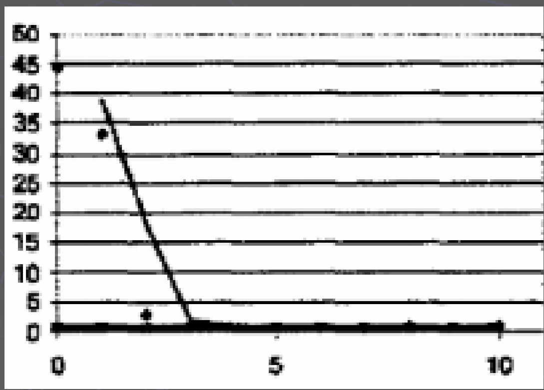
- Monitoring of performance: quality of communication link between independent stations and APs.
- Three MAC performance metrics evaluated:

1. PER: % of bad packets of all received packets
2. Throughtput-effective DR at receiving end
3. Ping time-round trip time for a 32B poll packet

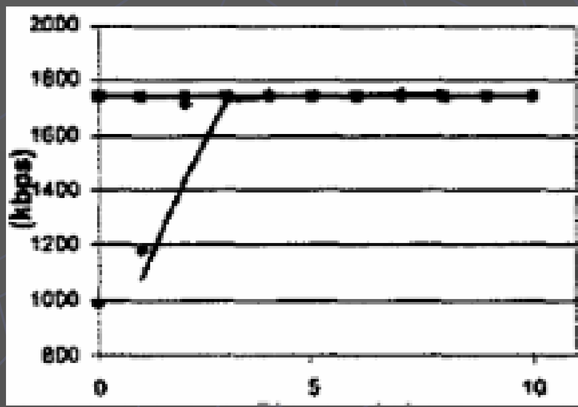
- 2 scenarios (over 6) yielded to conclusive results

Performance Metric results 1

-Network performance reduced
- At close range the effect of interferer decreases the performance because of probabilistic collision + some other effects
-It appears d=3m as distance beyond which no interference is seen



Packet cell rate of 802.11 with one data BT interferer (%)

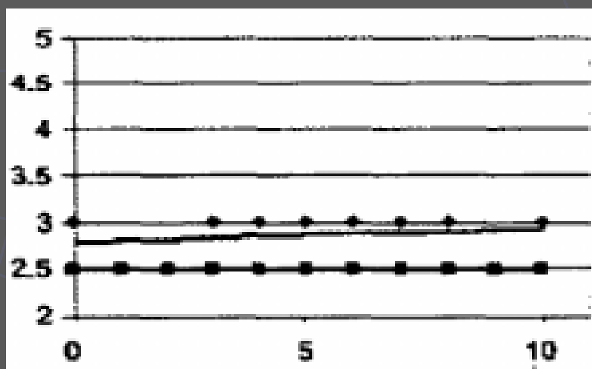


Throughput of 802.11 with one data BT interferer

Legend: continuos lines as reference, square: WLAN, other: BT

Performance Metric results 1

Ping time of 802.11 with one BT voice interferer



- Effect of one interferer**: both systems present good performance after 3m**
- Usable at smaller distances (around 1m) for low traffic situation (see ping figure)

Observations

- BT data exhibits higher degradation. BT voice exhibits lower degradation because of its lower piconet utilization.
- d=3m mark might be explained by the interferer's power inadequate to cause PER(?). It shows anyway the power sensitivity of the two standards.
- The variation of performances for the systems approaching the mark value could be different due to modulation technique(?)

- FROM OTHER SCENARIOS it appears that:
  - BT is fairly robust due to high hopping rate.
  - 802.11 seems to more vulnerable.

OVERALL RESULTS:

- Completely unfeasibility for BT & WLAN to operate simultaneously in proximity (on the same computer): PER=99%, throughput reduced to 0, any reliability for both.
- For more reliable services at least 3m distance needed.
- More exhaustive scenarios needed to be further investigated.

Interference: analytical analysis

- The BT interference on co-located IEEE 802.11b (at PHY and MAC layer) and the impact on the performance of 802.11b parameterized by:
  - DR & packet size of 802.11b,
  - # BT piconets,
  - piconet utilization: 0 (no transmission)..100% (constant transmission),
  - distance between piconets and 802.11b radios.

-Model with essential features of both systems at PHY and MAC layers.

-Statistical propagation model: PL, multipath fading (Rayleigh PDF), shadowing, noise (AWGN). A BT piconet in the vicinity (1-5m) of a 802.11 station: PL for both the same.

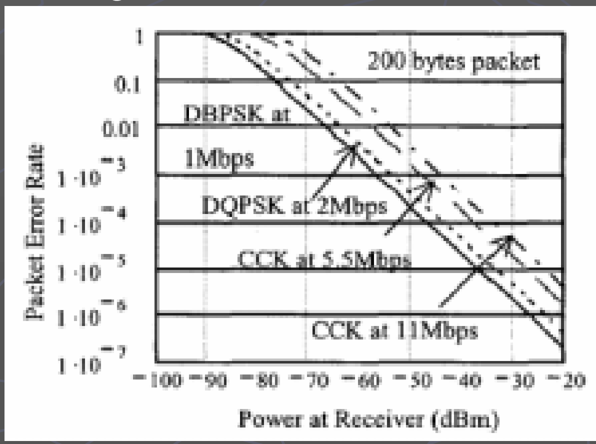
-PER of 802.11 per each DR (different channel coding and modulation scheme used for each DR) in presence of BT radios.

-Probability that BT packets will intersect in time and frequency.

IEEE 802.11 PHY analysis

- Performance of modulation in a fading channel:
  - -BER averaged over signal strength ranges.
  - -PER assuming that BER independent from bit to bit (valid in indoor): PER= 1- (1-BER)^m , m= #bits in the packet, (200..2400)B

Fig. PER vs. Power.



To have a low PER at high DR short distance of operation needed, otherwise retransmission rate required would be too high.

Collision analysis in small office

Needed a switching algorithm between the DRs to optimize system's total throughput.

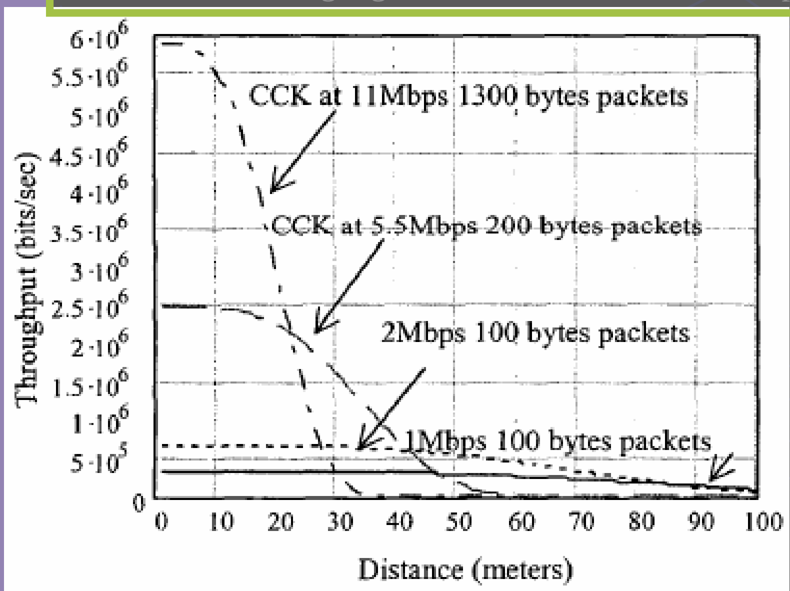


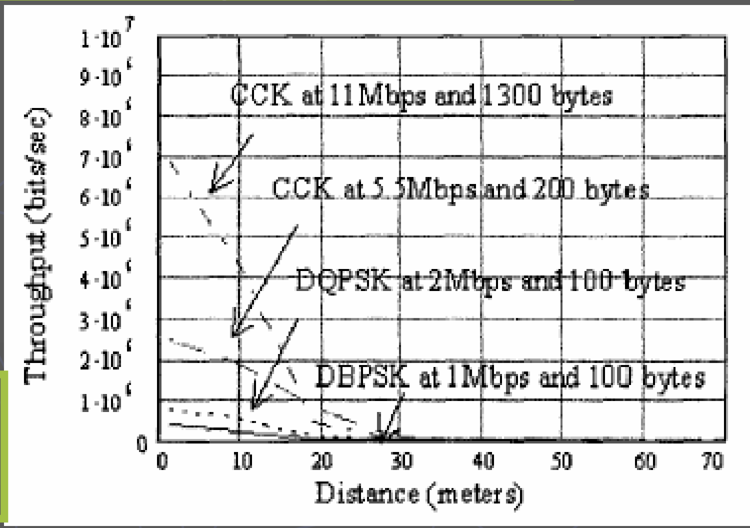
Fig. Throughput of 802.11 in presence of single BT piconet (utilization=30%). Packet size so that the individual throughput optimized for the region of operation where DR is most effective.

Efficiency of each DR vs distance separation of 802.11 transmitter, receiver:
-11Mbps gives the best result for a radius of 25m
-5.5Mbps best results for the next 20m

Collision analysis in open office

Fig. Throughput of 802.11, single BT piconet,u=30%, open office env.

Office layout with many STAs and a piconet associated with each STA uniformly distributed into the area (high density of piconets).
piconet interfering depends on the range 802.11 tx/rx distance.



Open office is an extreme case where drastic throughput degradation occurs.

Efficiency of each DR vs distance separation 802.11 (tx, rx):
-11Mbps the most effective due of shortest transmission packet time (lowest PER) in radius of 0-25m
-Beyond 25m the throughput is low for every DR: it suggests division of the open space into cells of 25m radius area, with AP in the center operating at 11Mbps with fragmentation size= 1300 B.

Collision analysis

- 802.11 transmissions suffer more than BT from 802.11. Reasons:
  - BT fast frequency hopping, combact interference jumping to a new frequency hop.
  - Area of operation in 802.11 much larger: 802.11 signal strength attenuates below the power of BT transmitter → more susceptible to interference.
  - BT packet smaller than 802.11: retransmission of Bt packet in case of loss for collision performed quickly.

-Probability of PER depends on the probability of collision in time and frequency and on the relative powers of the packets [3].

Experimental results in large outdoor open space

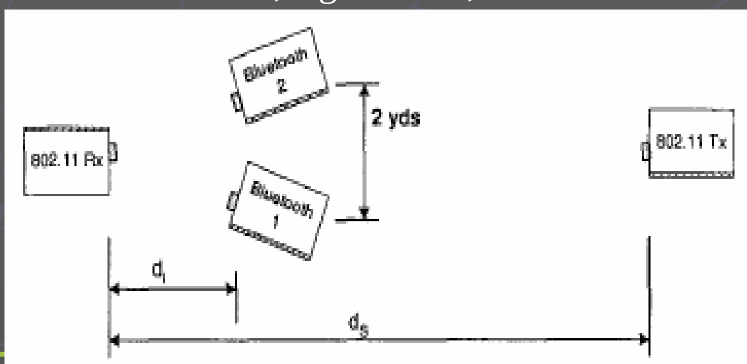
-[4] characterizes performance degradation of 802.11b devices through experimental results evaluated in large outdoor open space, football stadium.

- Since the power levels and channel effects cannot be regulated, the measurements are repeated also in a lab with tuned values. Less degradation is shown in this case.

Test bed
-BT devices on laptop: Digianswear BT PC cards, power output=20dBm
-Lucent/Orinoco 802.11b 11Mbps PC cards with power output=15dBm
-Varying SIR in controlled manner → measure PLR

Experimental setup [4]

-Steady traffic stream setup between the BT cards.
-Packet transmission (link tests) between 802.11 cards.
-Client SW manager gives statistics about the lost packets at 802.11 device at each DR, signal level, etc.



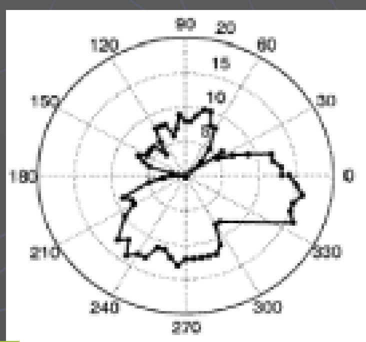
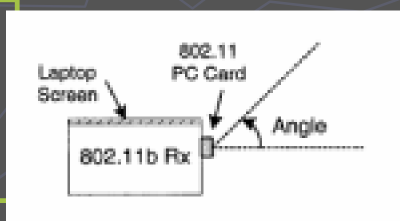
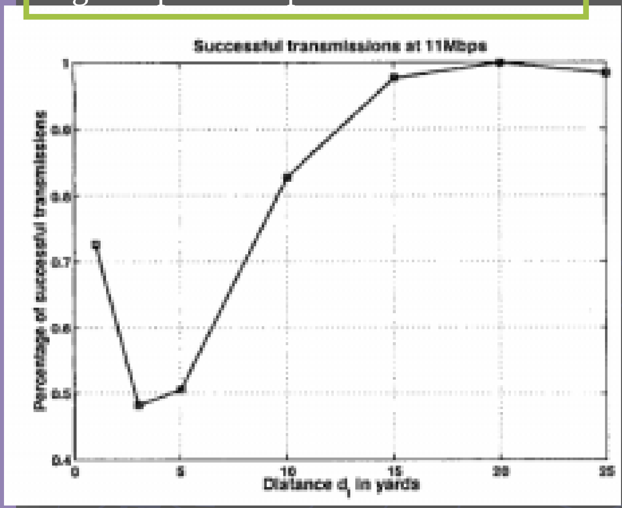


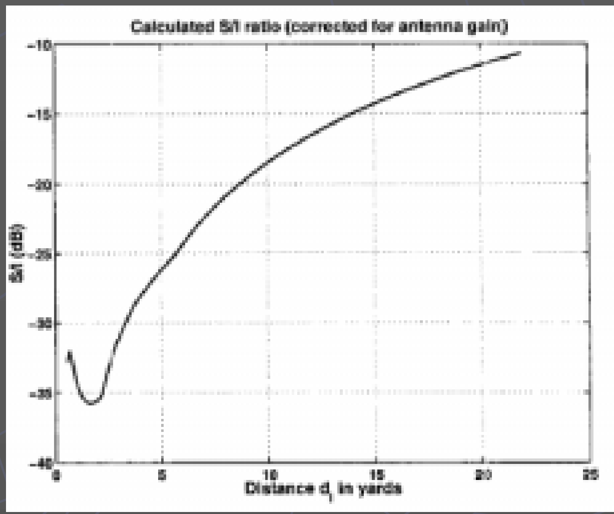
Fig. Experiment setup, Antenna pattern for 802.11 (dB) and Orientation for antenna pattern measurement.
- Varying d_S : signal level at 802.11 varies.
- Varying d_I: interference received at 802.11 changes



Experimental results in large outdoor open space [4]

Figs. Experiment performance results





- At smaller d_I: greater interference. Packet loss corresponds to decrease of SIR (2-ray ground reflection model).
- The improvement in SIR at very short distances due to receiver antenna pattern nulls in the direction of the interference.

Conclusions

- 802.11b has reasonable results even when BT interference is 10dB than desired signal. Packet loss is not the only form of degradation: MAC layer delays the transmission if it senses the medium busy.
- BT signal degrades rapidly when interfering 802.11b signal is as high as desired signal, For BT, where no carrier senses is performed, the attainable bandwidth is related directly to cell packet loss.
- Increased transmit duration increases vulnerable period for BT collision because covers the duration of a higher # BT hops. The loss of any part of packet causes the loss of entire packet the packet loss ratio is supposed to be higher (worst performance in presence of interference) for lower DR.

Coexistence mecchanisms

a) **Collaborative:** requires communication link between WLAN & WPAN networks in order of a cooperation on protocol level to minimize interference.
E.g.,: WLAN & WPAN embedded into the same device.

b) **Non collaborative:** no communication link between WLAN & WPAN networks.
E.g.,: WLAN embedded in laptop computer and WPAN module on PDA → independent adaptation.

Reducing mutual interference

Reccomended Practise of coexistence mechanisms by IEEE 802.15.2:

Collaborative: packet scheduling techniques to evoid packet collision

- AWMA (coordinated MAC layer for both radios)
- MEHTA (packet-by-packet basis decision of trasmission)

Non Collaborative:

- Adaptative packet selection and scheduling (APSS)
- Adaptative frequency hopping (AFH)

Abbreviations

AP Access Point

AWMA Alternating Wireless Multiple Access

BSSID Basic Service Set ID

CSMA/CD Carrier Sense Multiple Access /Collision Detection

CSMA/CA Carrier Sense Multiple Access /Collision Avoidance

CTS Clear to Send

CRC Cyclic Redundancy Check

FEC Forward Error Correction

GFSK Gaussian Frequency Shift Keying

HDLC High-level Data Link Control

ISM Industrial, Scientific and Medical

LLC Logical Link Control

Abbreviations

MAC Medium Access Control

NT Network

OSI Open System Interconnection

OUI Organizationally Unique Identifier

PCF Point Cordination Function

PDA Personal Digital Assistent

PHY Physical

PL Path Loss

PSK Phase Shift Keying

RTS Request to Send

SIFS Short Interframe Space

STA station

WPAN Wireless Personal Area Network

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Homework

1. Describe briefly the system performance degradation of IEEE 802.11b devices due to Bluetooth piconet presence in the nearby.

2. Describe briefly the important parameters to take into account for an accurate analysis of interference between the system IEEE 802.11b and Bluetooth piconets and their impact on the performance results.