Bluetooth Radio Network Performance: Measurement Results and Simulation Models

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When designing (standardizing) communication systems, simulations determine a large portion of the system parameters.

Verification required in testbed

- Validates simulation models
- Shows system performance
- Reduces the risk of unexpected behaviour
Outline

- Bluetooth
- Test set up
- Model generation
  - Noise limited scenario
  - Interference from IEEE 802.11b
  - Microwave oven interference
- Bit error clustering
- Summary
System under investigation: Bluetooth

- Short range cable replacement technology
  - Intended range: 10 m (with 0 dBm TX power)
  - Extended range: 100 m (power control compulsory)

- Global unlicensed frequency band (2.4GHz ISM, also used by IEEE 802.11b and microwave ovens)
  - 79 carriers of 1 MHz carrier bandwidth almost worldwide

- GFSK modulation, 1 Mb/s modulation rate

- Data and speech transmission possible
- Ad-hoc Network
- Master-slave-piconet concept
- FH/TDD channel
Test set-up

Recorded data for each packet:
- Time stamp (Packet index)
- Transmit carrier
- Access code/header/payload or no failure
- Payload error pattern (speech, SCO)
- Retransmission index (data, ACL)
Examples

BT-8T distance 5m, parallel antennas

BT-8T distance 12m, orthogonal antennas
Measurements

Variation of:
- Bluetooth link distance
- Antenna orientation
- Distance to interferer
- Type of interferer

For each set of parameters a large number of measurements have to be performed
Theoretical values (that are the basis for the simulations) consist of three parts:

1. BLR, FER = f(CIR)
   The same basis for all scenarios

2. CIR = f(d, P, antenna orientation, l(f_c))

3. Time behaviour of interferer
1. BLR, $FER = f(CIR)$

**Access code:** Specific encoding

**Payload:** uncoded

**Header:** 1/3 rate repetition code

**SCO packet** lost in case header or access code faulty (FER)

**ACL packet** lost in case header, access code or payload faulty on the forward link or the acknowledgement is lost on the reverse link (BLR)
1. BLR, FER = f(CIR)

BLR = f(d, l, f_c)

FER = f(d, l, f_c)

CIR = f(d, l, f_c)

Considers GSFK modulation gain and Rayleigh fading.
Noise Limited Scenario

$\text{CNR} = f(d, P/\text{antenna orientation})$

$\text{CNR}(P_{BT}, d_{BT}) = 10\log\left(\frac{P_{BT}}{\text{mW}}\right) - 40\text{dB} - 20\log\left(\frac{d_{BT}}{\text{m}}\right) - N$

Noisefloor $N = -91\text{dBm}$

40db path loss at one meter distance

$P_{BT} = 1\text{mW (parallel antennas)}, 0.5\text{mW (orthogonal antennas)}$

$d_{BT} = 5, 8, 10, 12\text{m}$
Noise Limited Scenario

4 allowed access code errors, sensitivity -73dBm
CIR = f(d_{BT}, d_{I}, \text{Antenna orientation}, f_c)

\[
\text{FER (d_{BT}, d_{I}) = } \frac{1}{79} \sum_{i=1}^{79} \text{FER}(\text{CIR}(d_{BT}, d_{I}, f_c)) \cdot \text{Prob}(f_c, \text{A/H})
\]
17 of 79 carriers are interfered
With tested load of 31%

\[
\text{FER} (d_{BT}, d_I) = \frac{1}{79} \sum_{c=1}^{79} \text{FER}(\text{CIR}(d_{BT}, d_I, f_c) \text{Prob}(f_c, A/H))
\]

\[
\text{FER}_{802.11}(d_{BT}, d_I) = \frac{17}{79} f(\text{CIR}(d)) \quad 31\
\]
Frequency behaviour of microwave oven
Microwave oven behaviour

- Transmit power frequency dependent
- Frequency is time dependent
  - Active only in the positive part of mains power circle (10ms of 20ms in Europe)
  - Sweeps over 61 carriers
- Microwave oven signal is very narrow band

Therefore the probability that Bluetooth packets are interfered is time and frequency dependent
Bit Error Clustering

- To show the (in)effectiveness of the optional 2/3 rate channel coding
- One parameter to determine the speech quality of CVSD encoded speech

\[ C = \frac{1}{14} \sum_{n=1}^{14} \frac{ACF(n)}{ACF(0)} \]

C=0 => 2/3 rate coding can correct all bit errors  
C>0 => 2/3 rate coding not effective
Bit Error Clustering

~2% of payloads with more than 3.3% RBER
Summary

- Comparison between Bluetooth radio network testbed and simulation results

- Noise limited scenario: Free space propagation, Rayleigh fading and antenna orientation have to be considered (parallel to orthogonal 3dB loss)

- Interference limited scenarios: Additionally distance to the interferer and the time-frequency behaviour has to be modelled
  - IEEE 802.11b: Constant bandwidth and transmit power plus activity factor
  - Microwave oven: Time-frequency dependent behaviour
  - Larger clustering values in case of interference and optional channel coding is not very effective