# Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

**Submission Title:** [Network-to-network interference measurements]
**Date Submitted:** [16 July, 2009]
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**Abstract:** [Network-to-network interference measurements for nearby, uncoordinated BANs, where the networks cause co-channel interference. Implications for interference mitigation]

**Purpose:** [To promote discussion of the dynamic channel model in 802.15.6.]

# Notes for revision 2

- Slides 15-18 added
  - Addresses questions of single-BAN interference (vs. multi-BAN collision)
  - Considers effect of collision avoidance
  - Demonstrates effect of weak SIR tolerance in receiver on number of free channels needed.

# Network-to-network interference measurements

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# Outline

- Network-to-network interference measurements
- Implications for direct sequence spread spectrum techniques

*More info:*

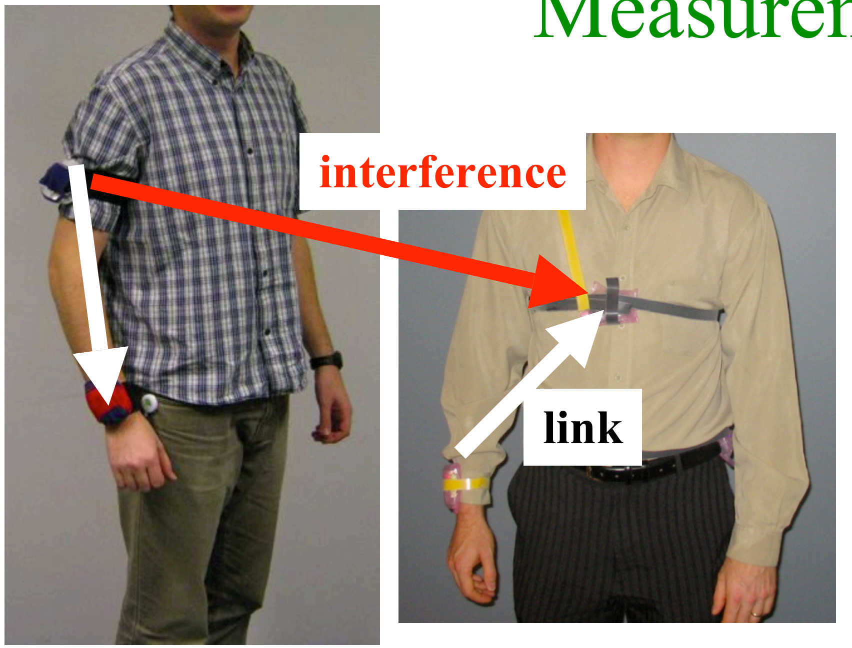
**Interference in Body Area Networks: Are signal-links and interference-links independent?,** Zhang, Hanlen, Miniutti, Rodda, Gilbert, *PIMRC 2009, to appear*

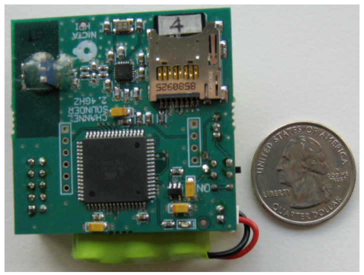
**Interference in Body Area Networks: Distance does not dominate***,* Hanlen, Miniutti, Rodda, Gilbert, *PIMRC 2009, to appear*

# Objective

- Addresses questions:
  - How severe is interference from adjacent body area networks?
    - We will show:
      - Typical BAN-to-BAN interference
      - Collective (10 users) interference.
  - Do we need to measure signal & interference simultaneously for Signal-to-Interference-Ratio estimates?

# Measurement Technique



Wearable channel measurement device

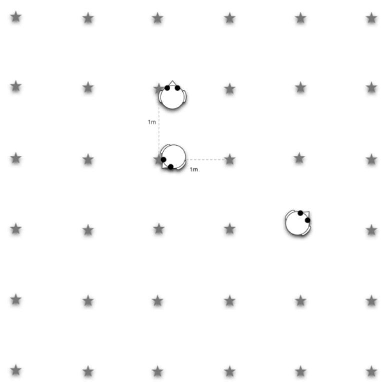
- 2360MHz Carrier frequency, 10kHz BW
- 0dBm transmit power, -95dB receiver sensitivity
- 60minutes of data with 5 test subjects walking in office environments
- Subjects wore one or two devices each

- Body surface to body surface: CM3, Scenarios S4, S5
- **And** Body surface to external: CM4, Scenarios S5, S6

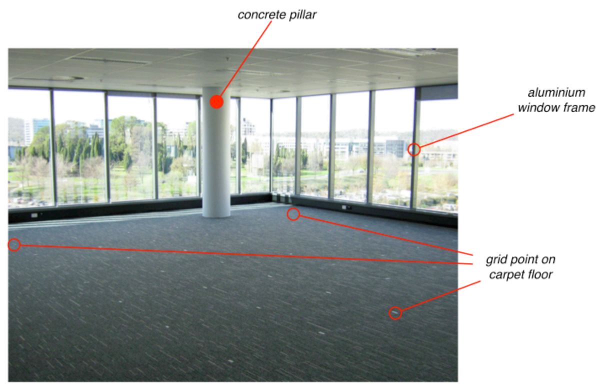
- Received Signal Strength Indicator (RSSI) quantifies attenuation
- On-body to on-body (person A to person A) link gives signal strength
- On-body to on-body (person A to person B) links give interference strengths

# Measurement Technique
# Scenario 1: random movement in office area

- 5 male subjects moving in pseudo-random arrangement
  - 6m x 6m grid layout with 1m gradation
  - Subjects stood at grid points and faced random directions
  - Subjects walked slowly between grid points at fixed time intervals
- Transceivers worn on upper arm, wrists and in hip pockets
- RSSI measurements give direct power ratio of signal and interference

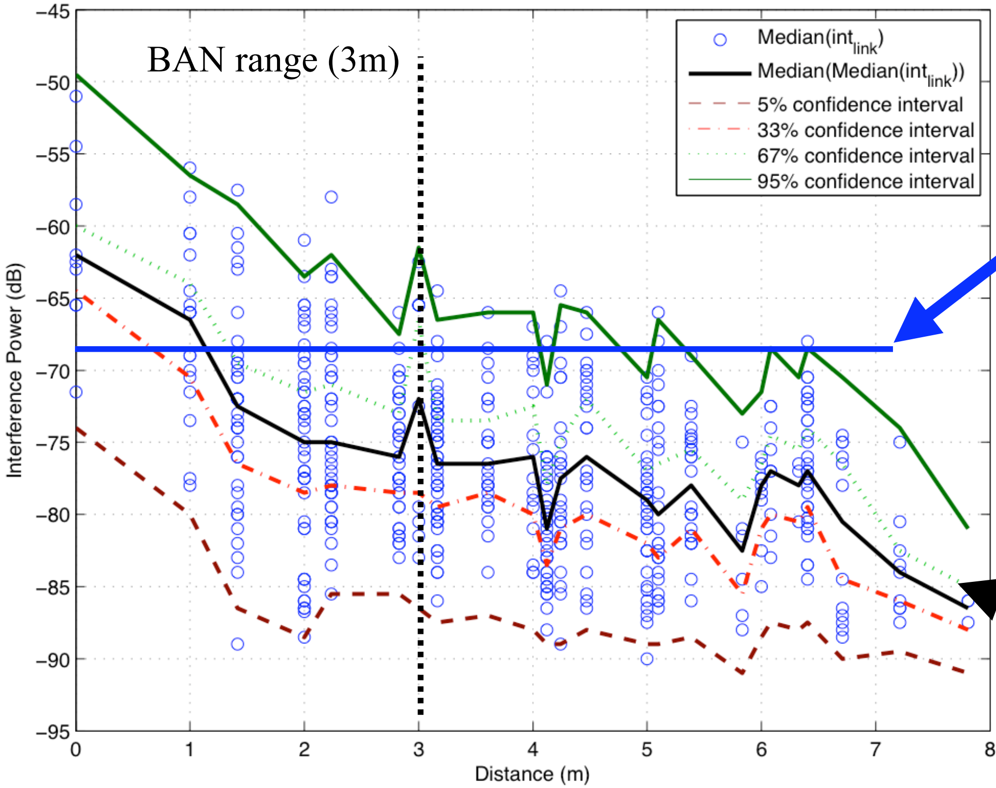


| Subject | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Tx | (1) right hip | (2) right hip | | | |
| Rx | (a) right shoulder | (b) left wrist<br>(f)* right hip | (c) left hip | (d) left hip | (e) left hip |



# Interference Power vs Distance

***No strong correlation between distance to interferer and received interference power***




Median operating point at 0m is -67.7dB

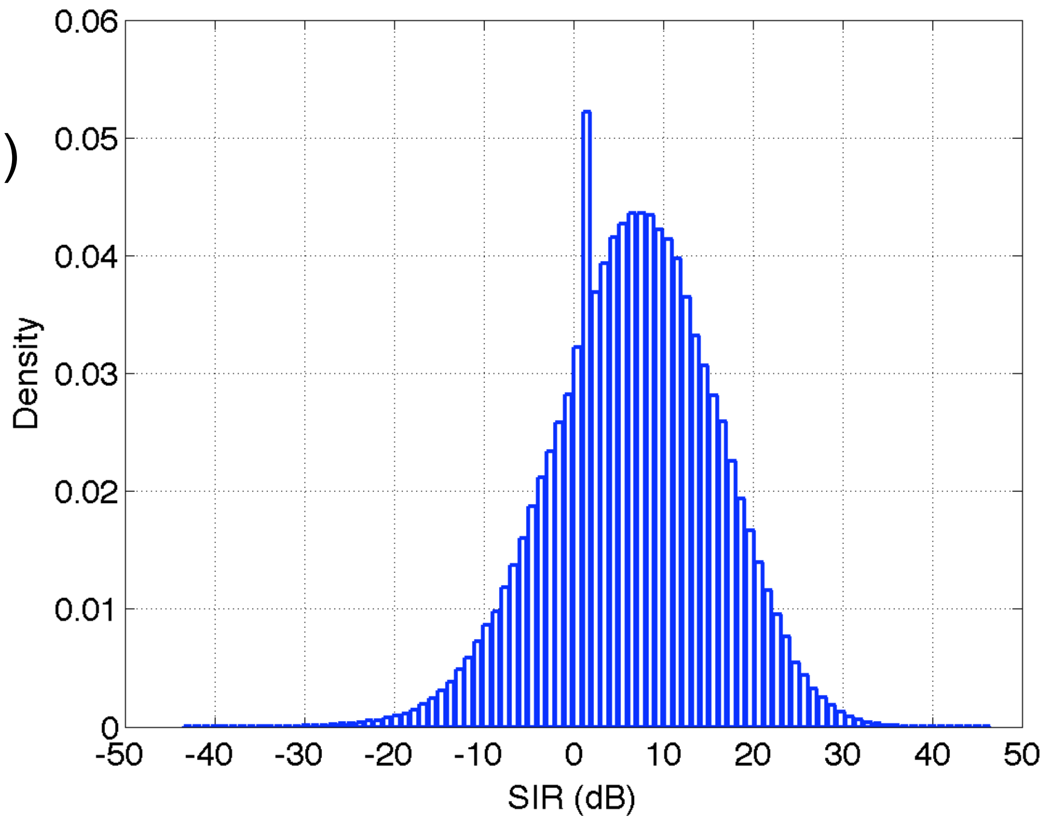
Median trend line given by:

$$-2.1D_{\text{meters}} - 67.7\text{ dB}$$

**Interference in Body Area Networks: Distance does not dominate**, Hanlen, Miniutti, Rodda, Gilbert, *NICTA tech-report CRL-2175*

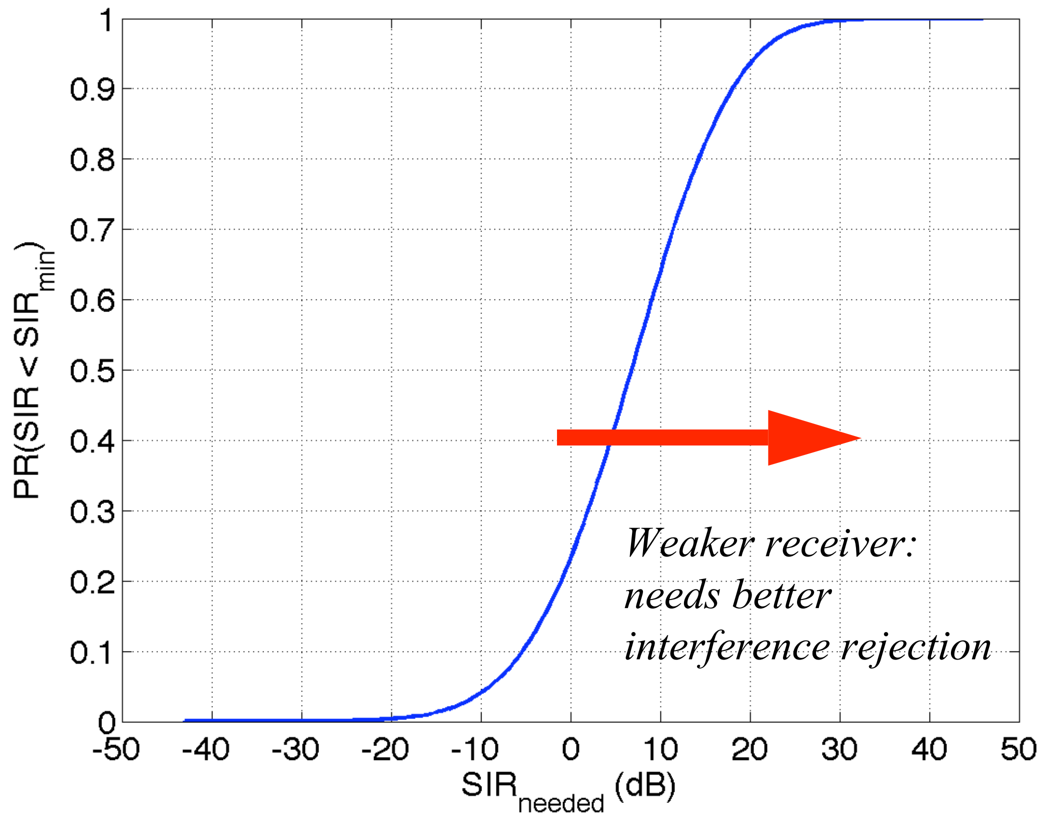
# PDF of Signal-to-Interference Ratio

- Assumes all users on same channel
- Gives SIR for single (typical) interferer
- Median single-interferer SIR: +7dB



# Outage probability

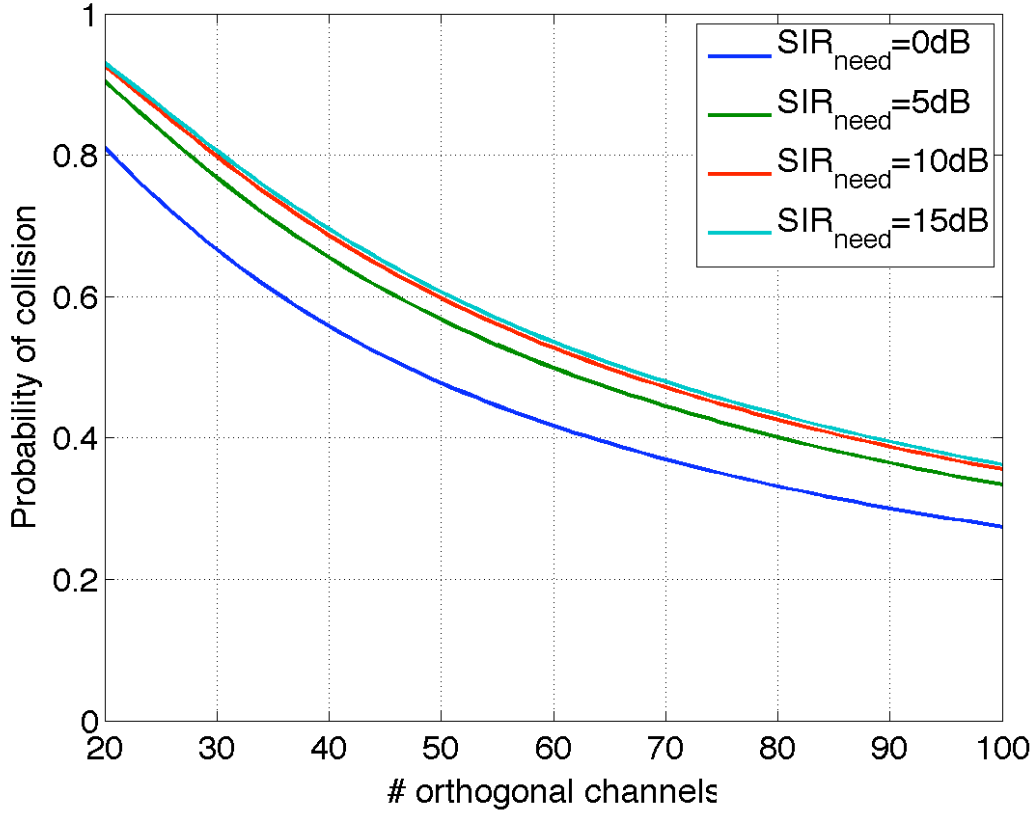
- SIR for a single user, and a single typical interference
- $SIR_{NEEDED}$ gives minimum SIR receiver can tolerate
  - When sample SIR is below $SIR_{NEEDED}$ the receiver is in outage



# Instantaneous collision probability for 10 users with N free channels

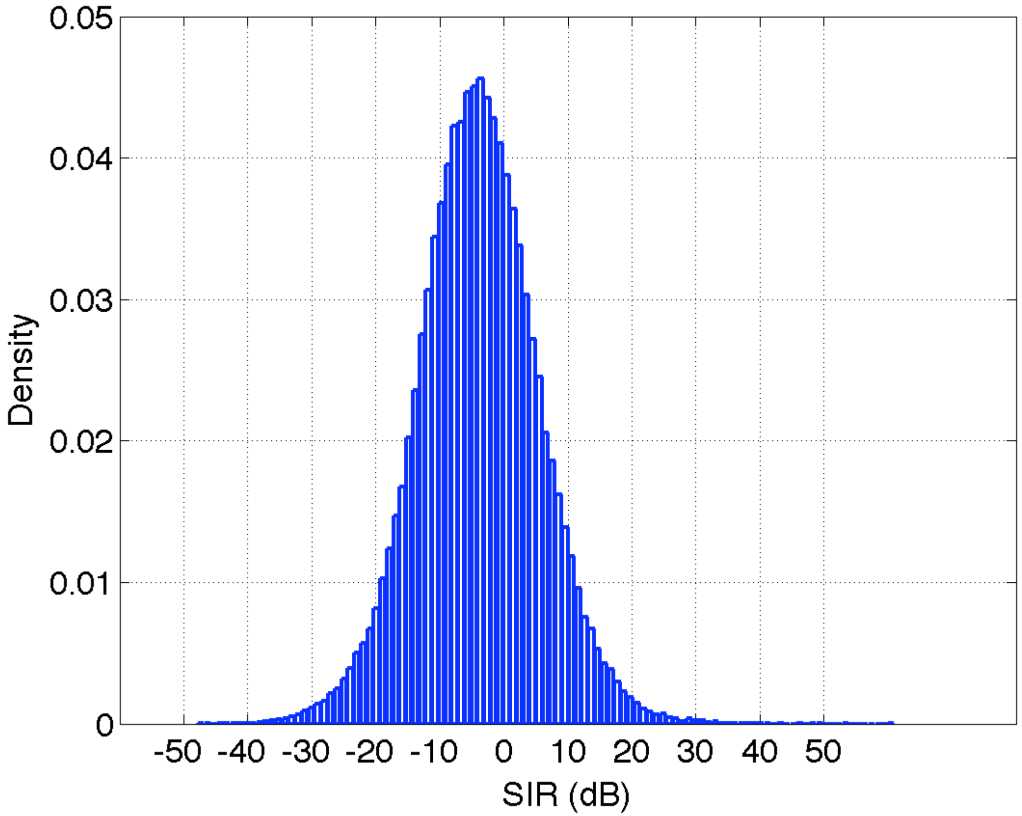
Assume: each BAN occupies a (whole) channel;
each BAN is assigned a channel at random (from all possible)

- Given n channels and q users, the probability of at least 2 BANs in same channel (overlap) may be found numerically
  - Solution to "birthday paradox"
- AND If any overlapping user has SIR below $SIR_{NEEDED}$, a collision occurs (data loss due to interference or re-assignment of channel needed)



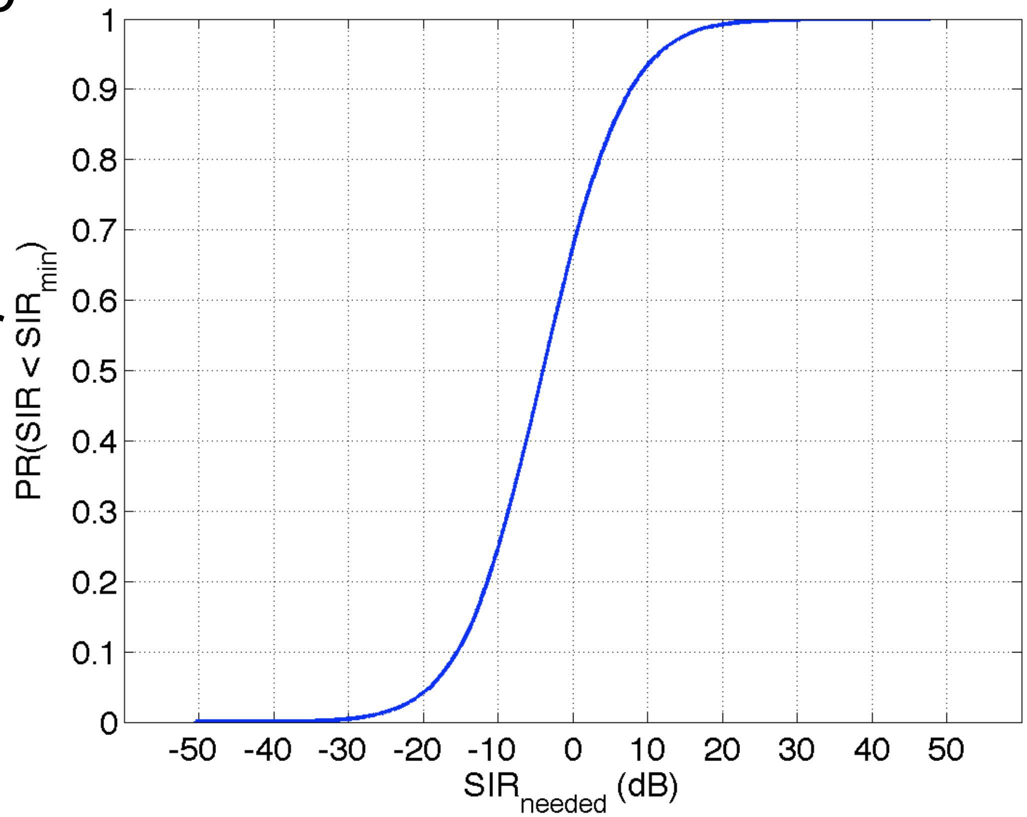
# 10 users modeled SIR

- Assuming 10 users in same channel
- Non-coherent (random phase) signal addition
- Median operating point:
  - 9-interferer SIR, -4dB
  - Log-normal profile



# 10 user model CDF

- SIR for a 1 user, and 9 co-channel interferers
- $SIR_{NEEDED}$ gives minimum SIR receiver can tolerate
  - When sample SIR is below $SIR_{NEEDED}$ the receiver is in outage



# Model for multiple users

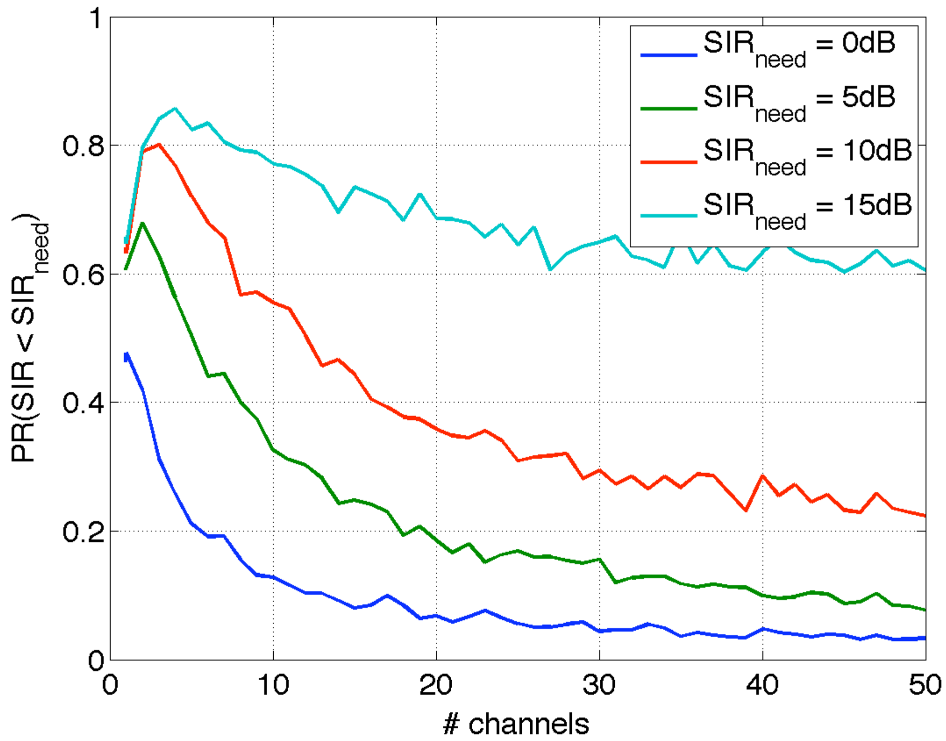
- Measured RSSI is a power measurement
  - Convert to signal amplitude
- Apply random phase (uniform between 0 and 2pi) to 9 randomly selected RSSI signals
  - Had 5 interferers in experimental results
  - Take 9 (random) samples of these measurements to generate 9 virtual interferers
- Sum to give total interference
- All calculations in linear domain (convert to dB only at the end)

# Numerical Experiment Setup

- N free orthogonal channels
  - Each user only needs one free channel to communicate
- 9 interferers independently assigned channels from {1,N} *uniformly at random*
  - models uncoordinated networks.
  - Each interferer has randomly assigned Interference Power from measurement experiments.
  - Interference Power adds non-coherently
- User randomly assigned a channel k from {1,N}
  - models non-coordination between networks.
  - Gives lowest probability of collision (vs any other channel assignment)
- IF the SIR in channel k is below $SIR_{NEEDED}$, then user cannot receive successfully. We consider two scenarios:
  1. User does not move to new channel: gives probability of collision when users do not apply collision avoidance
  2. User tries new channels for up to T attempts (until SIR high enough)
     - assuming all interferers remain in their channels (only the user changes channels).

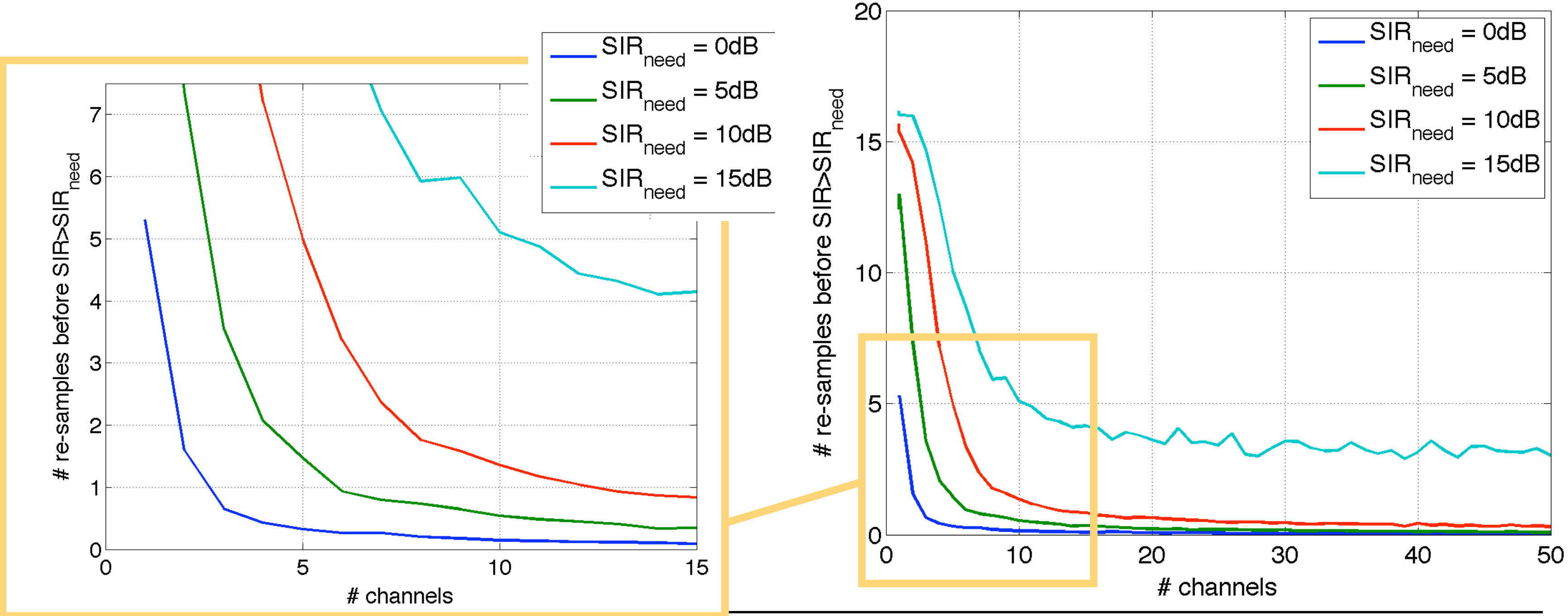
# Instantaneous collision probability for 1 user, 9 interferers and N free channels [numerical]

- Shows probability of channel for user 1 being **occupied**
- Occupied:
  - interferers are present in the same channel AND the given user has SIR below $SIR_{NEEDED}$
  - Thus a collision occurs
  - data loss due to interference or re-assignment of channel is needed)
- Does not consider collision avoidance (next slide)



# Expected number of re-tries until a clear channel is detected (overhead) [numerical]

- Expected number of additional samples (after first attempt) to find an un-occupied channel. For values approaching zero, the overhead due to SIR is small.
- Single user applies collision avoidance to find new (clear) channel
- All interferers remain constant: same power and same channel
- Plot on left shows zoomed region.

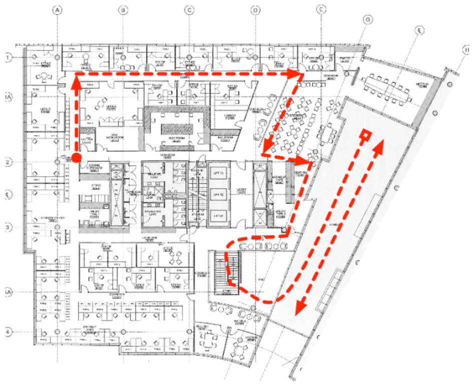


# Implications

- Channels are orthogonal, not necessarily frequency dependent.
  - **However**, as an example, consider 10x 1MHz BAN's with several orthogonal 1MHz channels and 1 BAN-of-interest. (implications are identical if "frequencies" replaced with "codes" or "time-slots" etc)
- With 15 channels (15MHz) the overhead of the $SIR_{need}$=15dB receiver is still 4x (total of 5 channel samples before expected success)
  - 15 channels and only 10 users means approx. 5MHz resources are "wasted" -- they have to be kept "free" to reduce probability of collision
- For the same number of re-tries (4x overhead), a $SIR_{need}$=10dB receiver can operate with 6 channels
  - Ie. A 1MHz BAN can co-exist with 9 other 1MHz BANs in only 6MHz of "free" space, if it uses a 5dB "better" receiver. A "better" receiver is one which has "better" interference rejection.
  - Ignores collisions between other interferers
- If the number of channels and the number of BANs are equal (channels = 10) then
  - $SIR_{need}$=15dB needs approx. 6 channel samples (1 + 5 extra)
  - $SIR_{need}$=10dB needs 3 channel samples (1 + 1.5 extra)
- A weaker receiver needs either more "free" channels (wasted resources) or more re-tries (wasted time + sample power) to achieve necessary SIR.
  - Does not hurt other networks, but implies a BAN with weaker receiver will be in outage more often.
- $SIR_{need}$=15dB receiver is substantially worse than other receivers due to (almost 1) probably of outage from CDF.

# Measurement Technique
# Scenario 2: walking in office area

- 5 male subjects walking in office
  - Movement constrained by corridors, doorways & stairs.
- Transceivers worn on wrists, in hip pockets, jacket and shirt (check) pockets
  - 2 subjects with on-body links
  - Channel sampled every 10ms

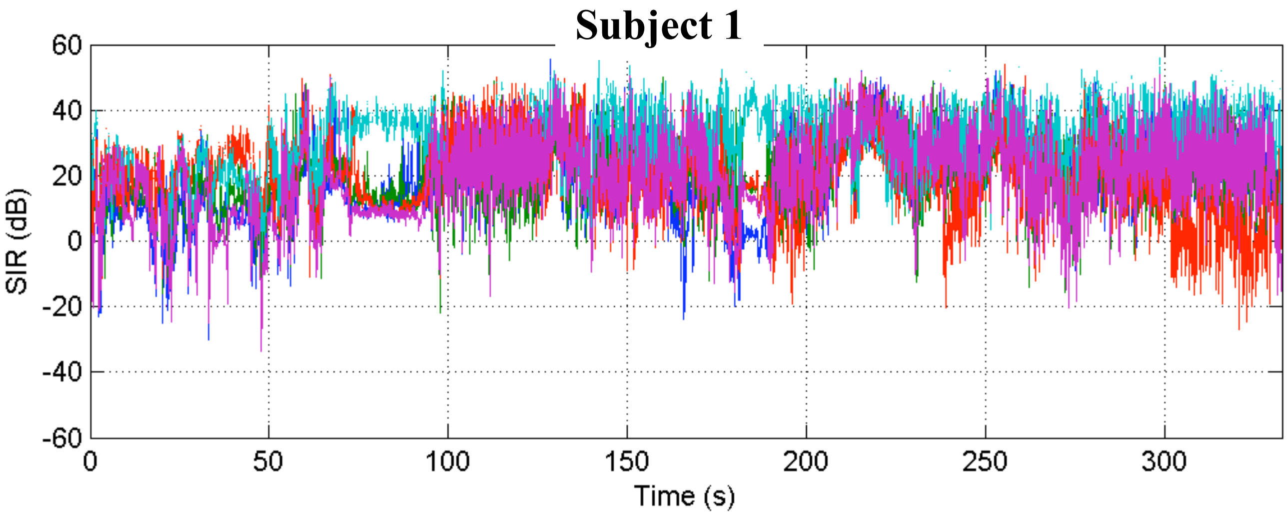


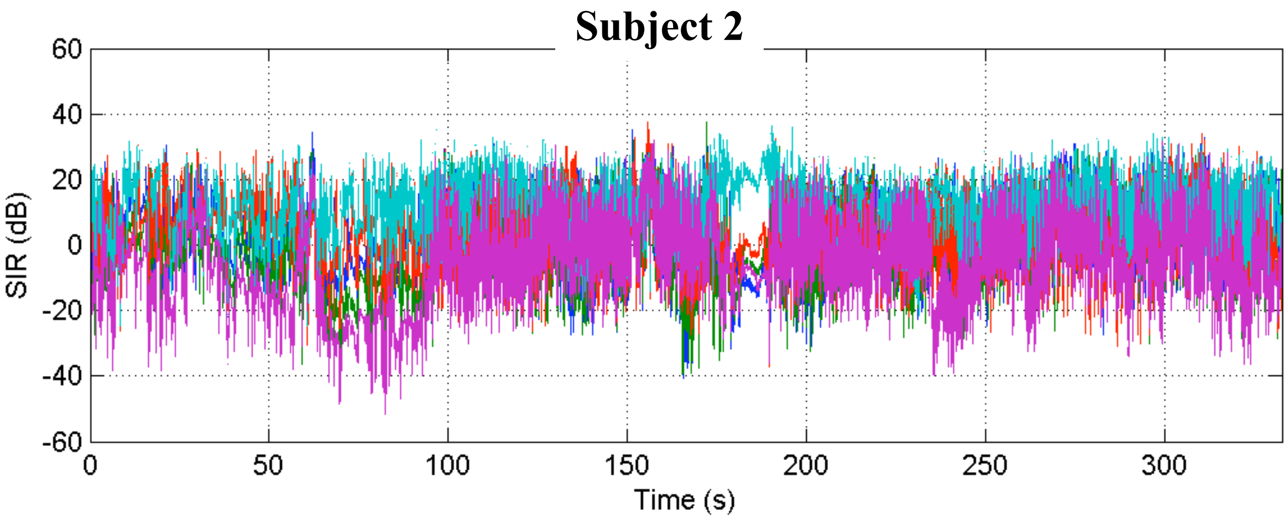
*Signal strength and interference strength are time-independent over timeframes of <u>more than a few seconds</u>*

| Person | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Tx | left wrist | left wrist | | | |
| Rx | left hip pocket | Right Hip Pocket | Jacket Pocket | Jacket Pocket | Check Pocket |

**Interference in Body Area Networks: Are signal-links and interference-links independent?,** Zhang, Hanlen, Miniutti, Rodda, Gilbert, *NICTA tech-report CRL-2177*

# SIR over time



# Implications for Direct Sequence Spread Spectrum

- Difficult for networks to collaborate, cannot do conventional power-control
- Near-far issue a known problem for DS-SS
  - Also: Asynchronous nature of networks
  - Combined interference vs probability of intercept

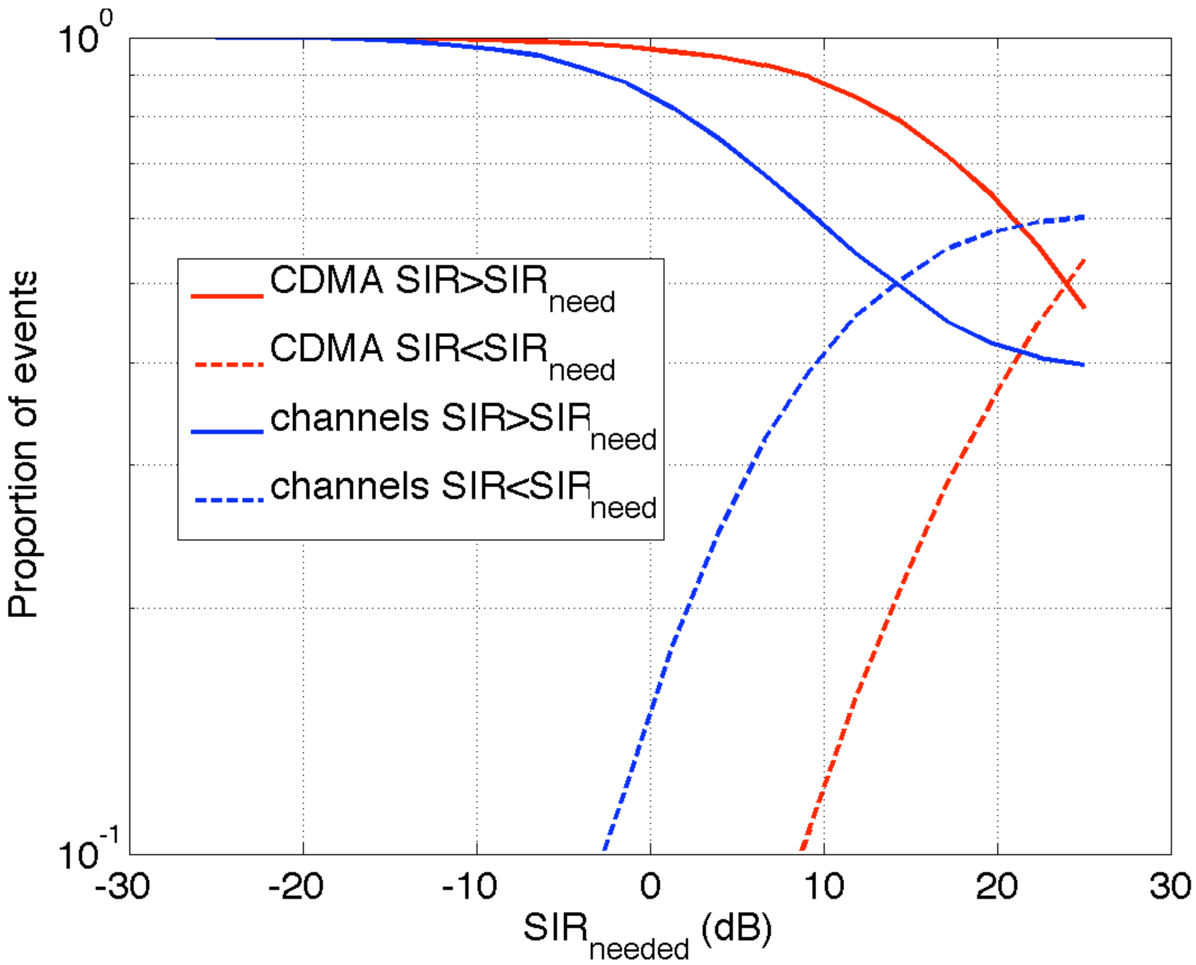
# Simulation for SIR and DS-SS

- Compared SIR receiver capability with fixed channelisation vs DS-SS
- Channel uses Scenario 1, with 10 BANs (9 interferers)

- DS-SS
- Optimized length 7 codes
- Codes assigned at random to each BAN
- Asynch arrival
- Interference power adds (random phase) for 9 interferers
- IF SIR < $SIR_{needed}$ THEN record outage.

- M-fixed channels
- BAN assigned at random to a channel
- Interference in each channel adds (random phase) for K interferers
- IF SIR < $SIR_{needed}$ AND channel equals user's channel THEN record outage.

# Simulation result



# Summary

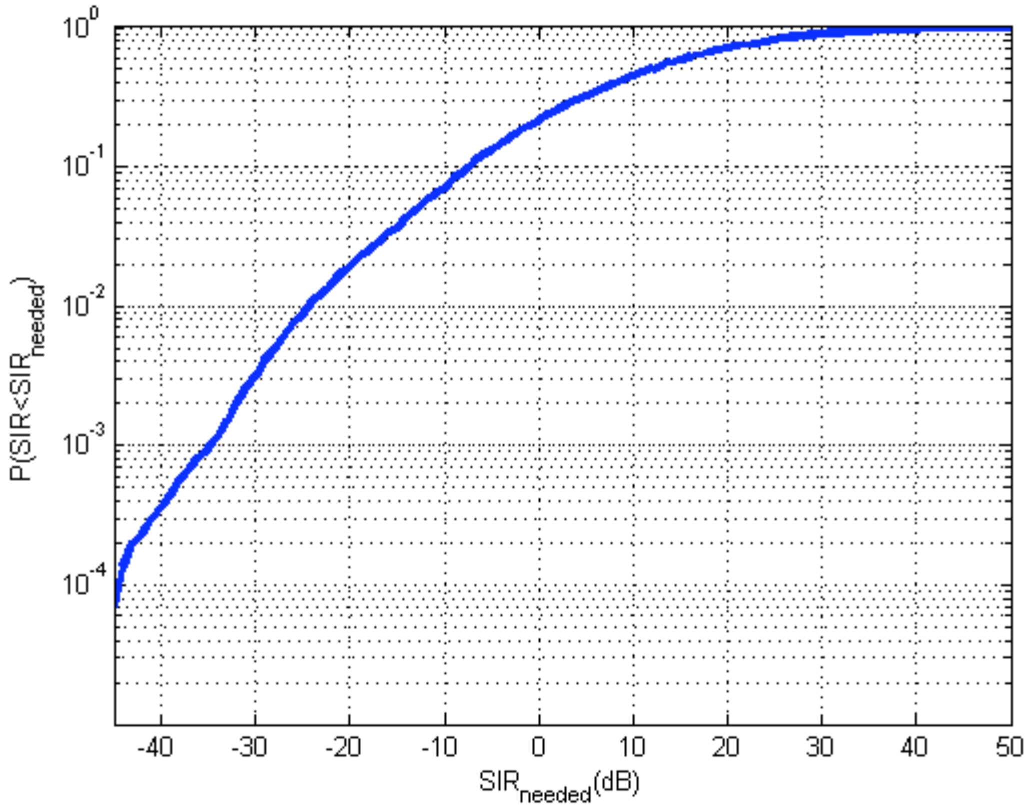
- We have measured co-channel interference in office environments
- Interferer power: Path-loss due to distance overwhelmed by SIR variability
- Signals and Interferences are independent in macro-scale (1 to 10’s of seconds)
- SIR variability causes substantial near-far issues
- Interference mitigation via DS-SS compared with fixed orthogonal random channels
  - appears robust when tested on measured and simulated multi-user interference.

# Appendix 1:
# Time-effects of “office traffic”

# Single-user SIR outage probability [Scenario 2]

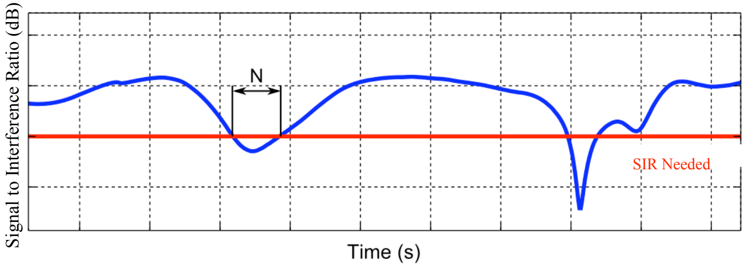
- Probability of a **sample's** power being below Rx sensitivity

- SIR for a 1 user, and 1 co-channel interferer
- $SIR_{NEEDED}$ gives minimum SIR receiver can tolerate
  - When sample SIR is below $SIR_{NEEDED}$ the receiver is in outage




Median SIR point is 12dB

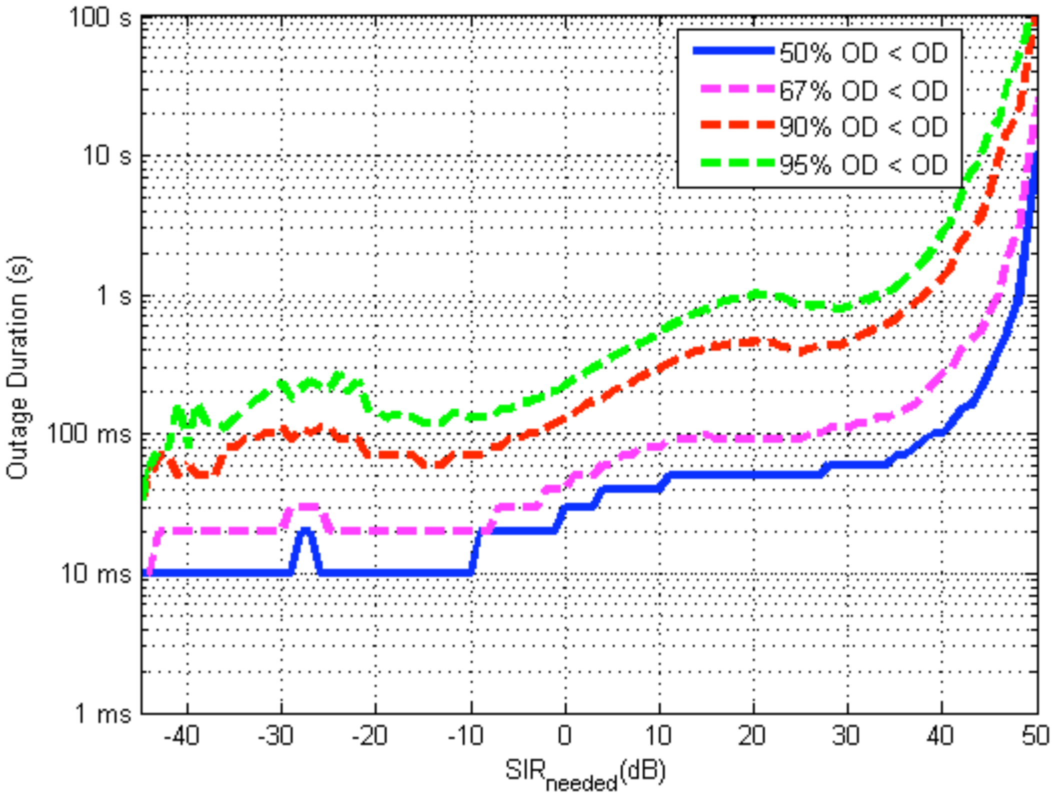
# Outage duration




- Systems must cope with losing N seconds of data, X% of the time due to co-channel interference

$SIR_{NEEDED}$ gives minimum SIR receiver can tolerate

X% of outages last less than N seconds



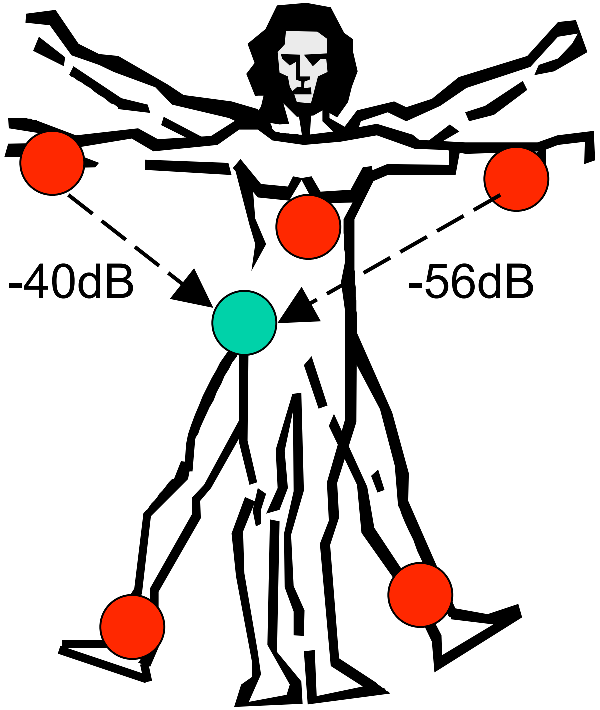
# Castalia BAN examples

Results from the complex channel modelling with some simple traffic scenarios.

Castalia software V2.1

# Scenarios setup

Six nodes: 1 sink (right hip), 5 transmitters (around the body)




Wireless channel: Average path losses measured in testbed + temporal variation (parameters extracted from real testbed)

Radio: 1Mbps, PSK, -95dBm sensitivity, -20dBm TX power

Scenarios run for 100sec, packets 140bytes

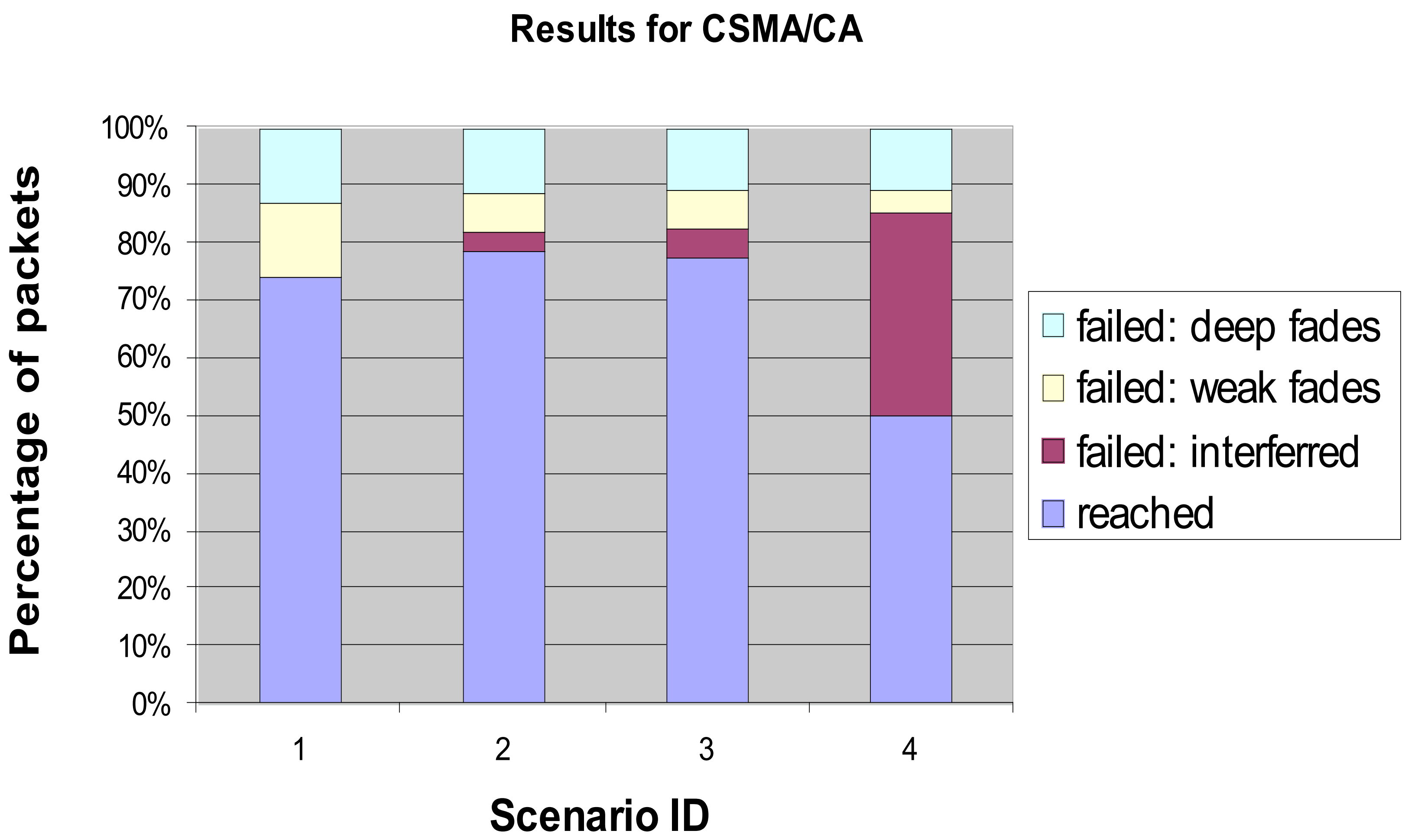
1) Only node 3 sending at 10 packets/sec
2) All nodes sending at 2 packets/sec
3) All nodes sending at 20 packets/sec
4) All nodes sending at 200 packets/sec *

* requires 1.1Mbps total throughput

# Questions to answer

- How many packets get lost due to temporal fading?
- How many failed due to deep fades and how many failed with a probability of reception > 5% (weak fades)?
- Is there significant interference (despite CSMA) due to temporal hidden terminal problems?

# Results for CSMA/CA

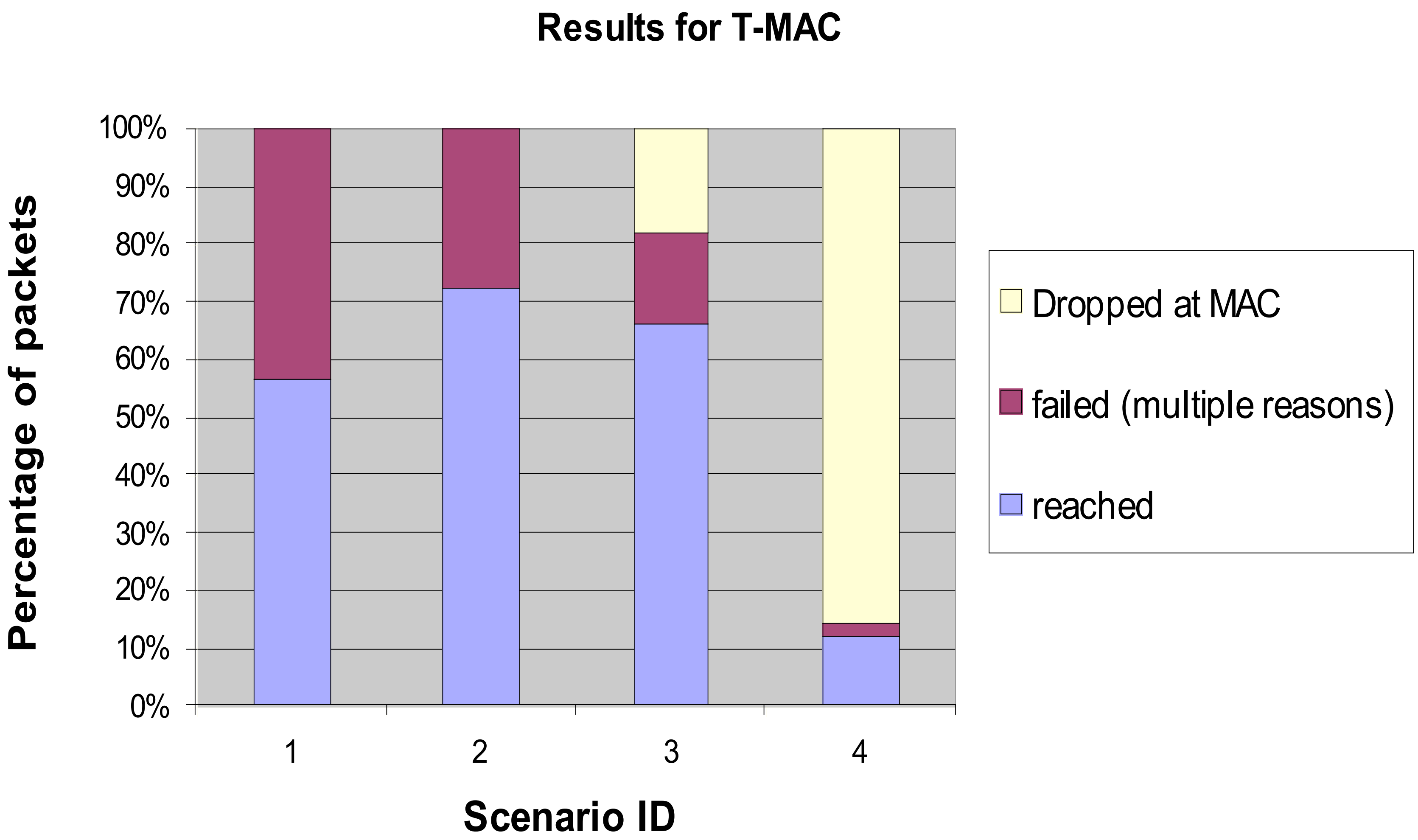


# More questions

- Would a ACK-retransmission scheme (max 2 times) fight temporal fading?
- Would an RTS-CTS scheme solve the problem of interference and temporal hidden terminal problems?
- Would it efficiently handle high loads?
- Could an adaptive duty cycling scheme with time-sync be able to cope with high loads?

For all the above try T-MAC

# Results for T-MAC



# Appendix 2 summary

- Simpler MAC's may be more robust under high channel variability
  - Non-intuitive results for highly variable channels.
- In high-data rate, and high channel-variability, RTS-CTS-data-ACK system may be detrimental.