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

Submission Title: [Sleeping channel measurements for body area networks]
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Abstract: [300+ hours of sleeping BAN channel measurements with characterisation of data in terms of outages with respect to receiver sensitivity. Showing that channel outages are greater than 10% with -100 dBm receiver sensitivity.]

Purpose: [To help design and evaluate BAN systems.]

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Sleeping channel measurements for BAN

[Jan 2010: added appendix]

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Outline

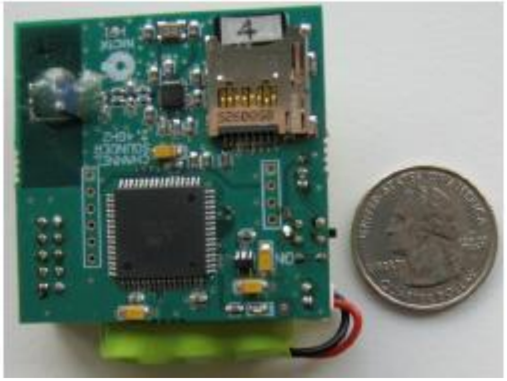
- **Motivation:** People have asked about what happens to the BAN channel when people are sleeping
  - Have done some sleeping measurements
  - People at home in bed (not hospital)

- Analysis:
  - Channel gain distribution
  - Outage probability
  - Outage duration

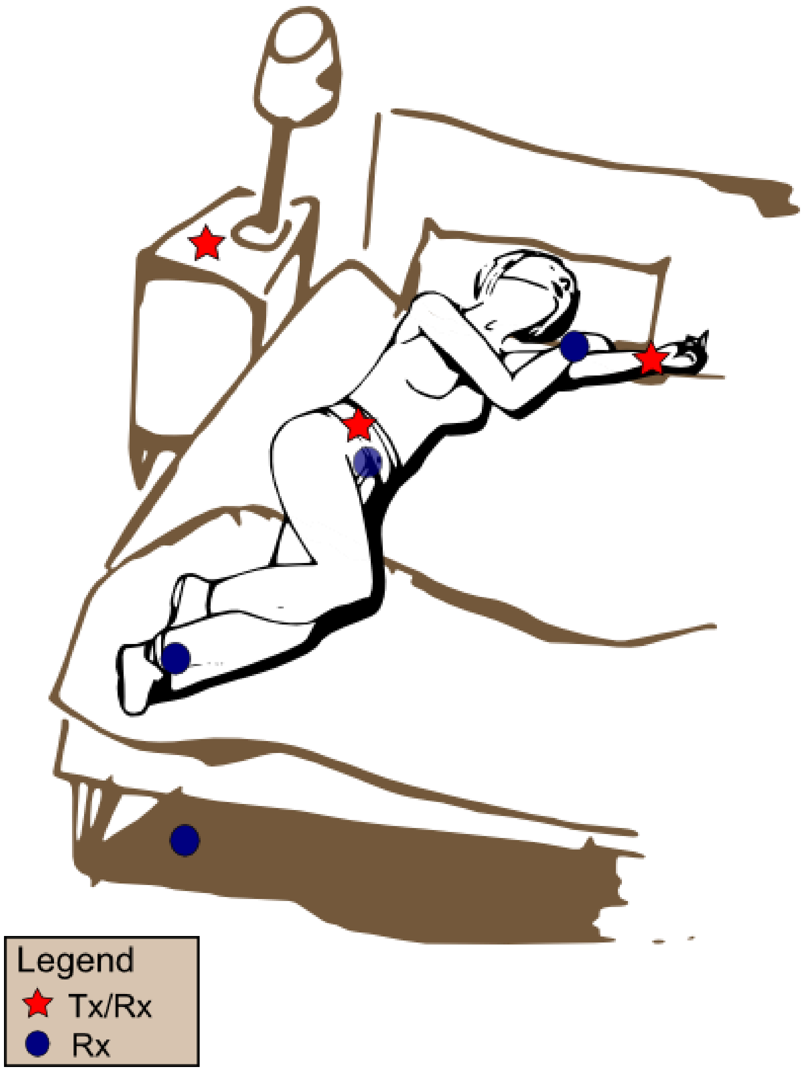
- *Outage = Received power < Receiver sensitivity*

Experiment setup

- Using NICTA's body-worn "channel sounder" (same one used in previous measurements)
- Measured people sleeping/lying in bed
  - Majority of data is for people sleeping
- 12 subject measurements (8 different adults)
  - Each measurement 2 hours or more (over 300 hours in total)
  - Just outside 2.4 GHz ISM band (to avoid ISM interference)
  - 0 dBm transmit power
  - RSSI sampled every 15 ms
  - 183 link measurements
    - 85 on-body to on-body
    - 98 on-body to off-body



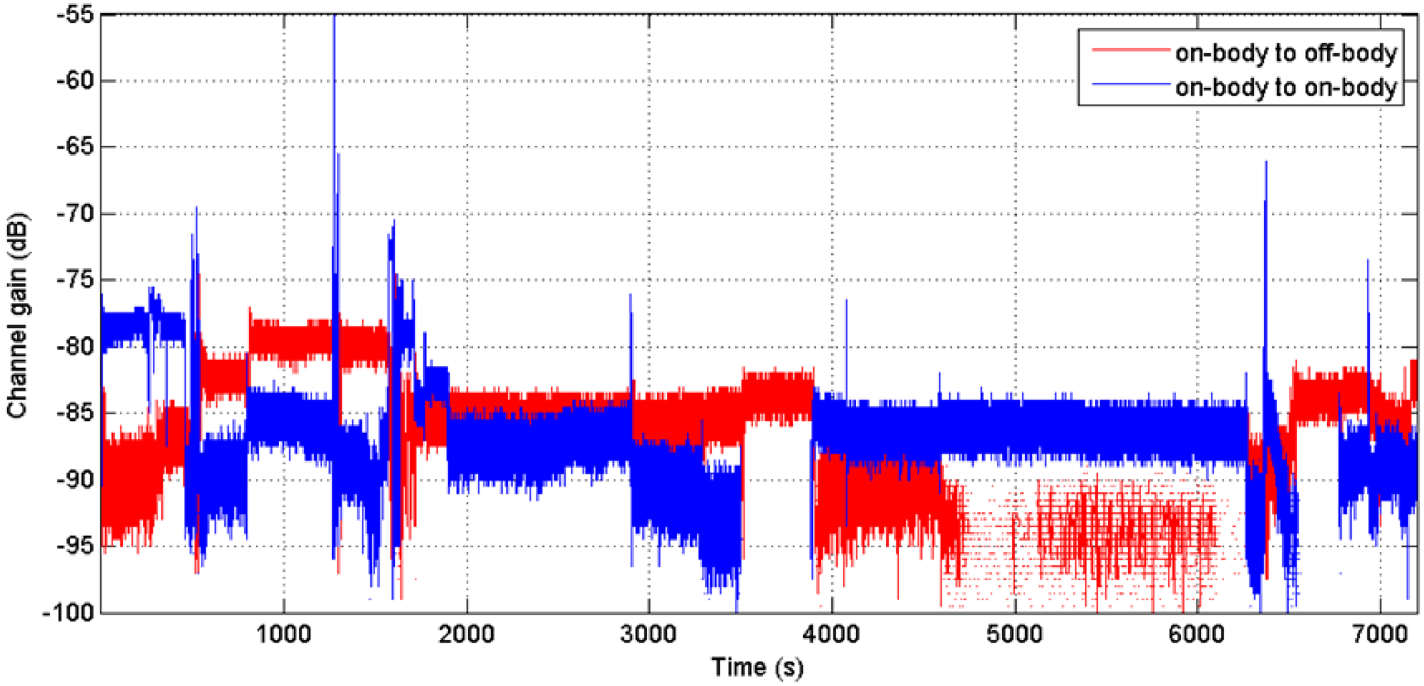
Measurement positions



Device positions	Device type
Next to bed (head)	Tx/Rx
Left wrist	Tx/Rx
Hip (front)	Tx/Rx
Next to bed (foot)	Rx
Right wrist	Rx
Hip (back)	Rx
Left ankle	Rx

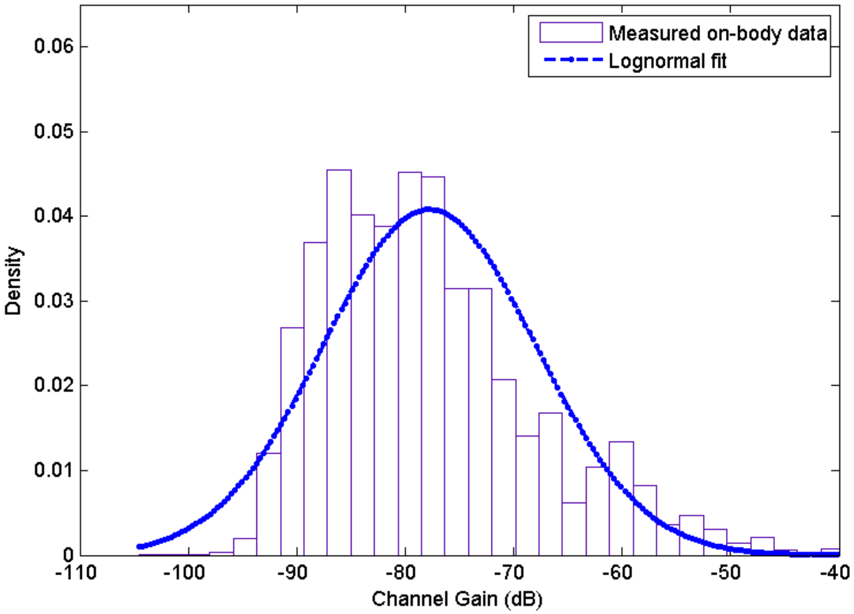
Transmitting devices also receive packets from all other transmitters. Physically they are the same, but they run different firmware

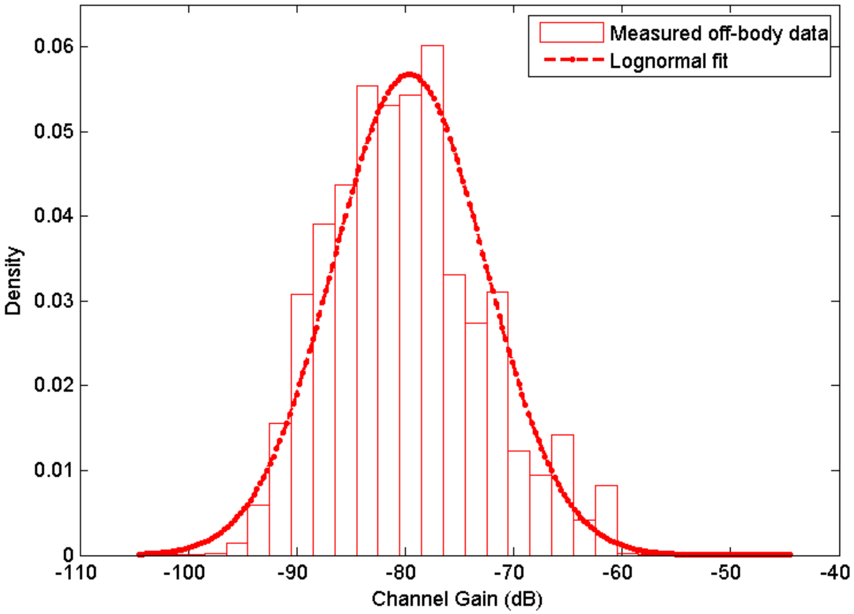
Typical measurement (example)



- General trend is for long periods where RSSI is stable
- Gaps in figure correspond to RSSI dropping below channel sounder receive sensitivity (approx: -100 dBm)
  - Including all data, this occurs 14.8% of the time for on-body and 14.9% of the time for off-body channels

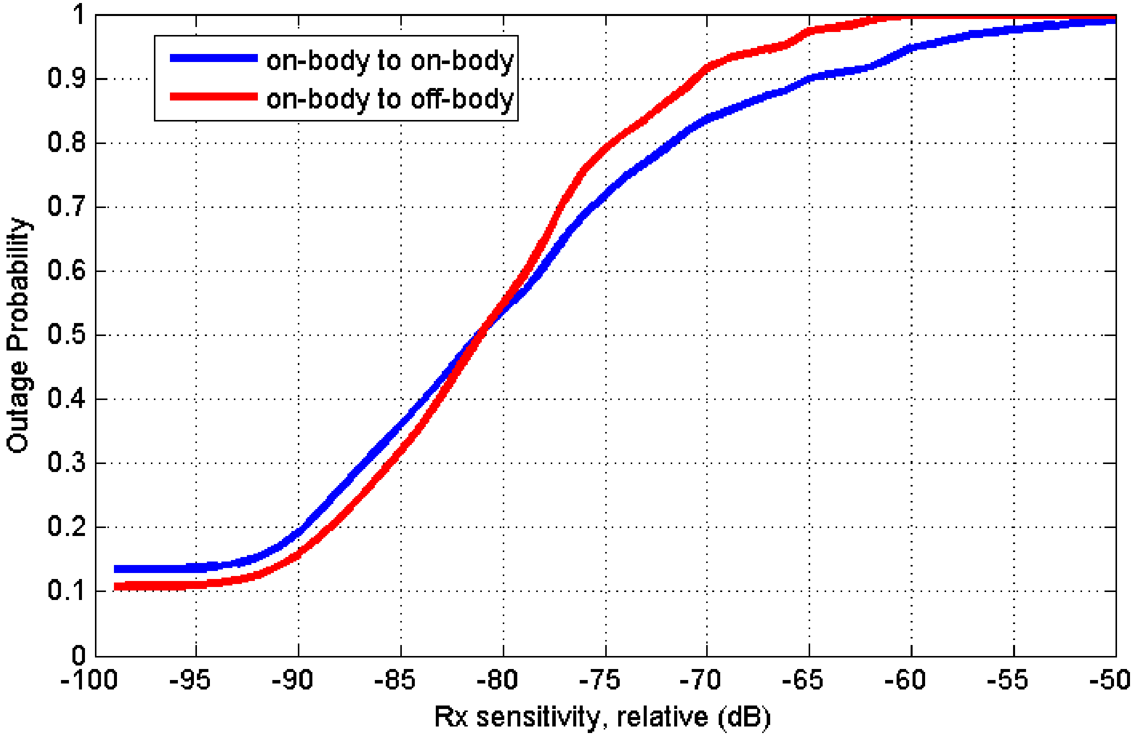
Channel gain distribution





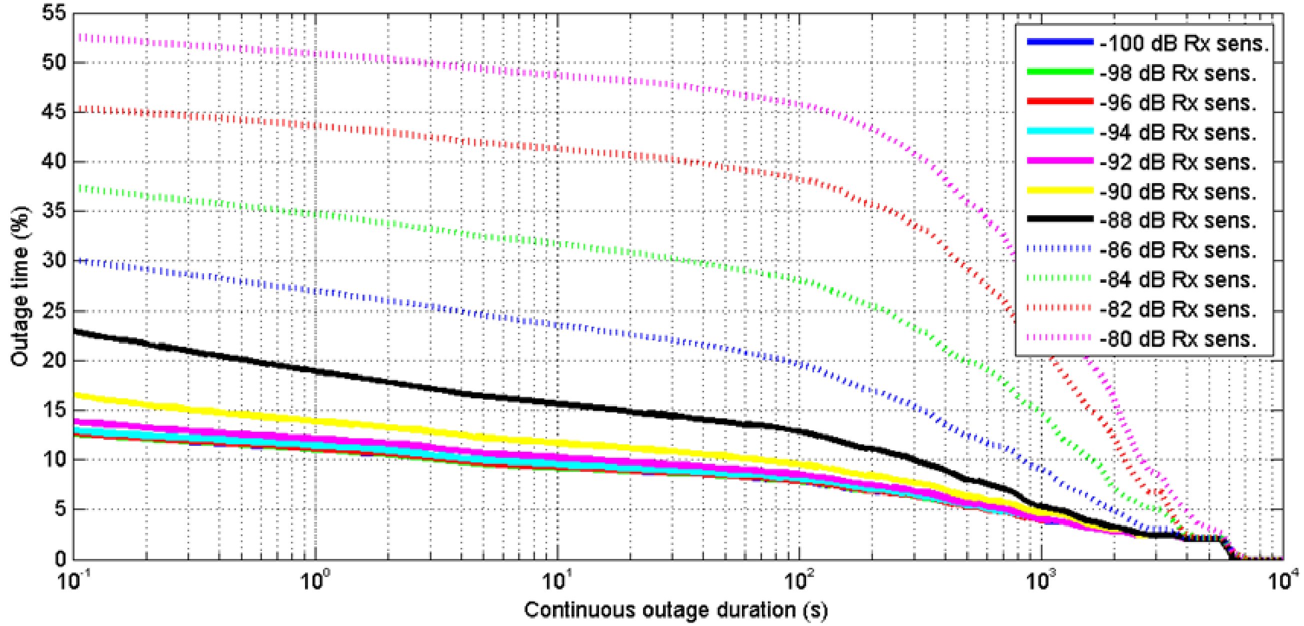
- Lognormal distribution is best fit
- Median channel attenuation:
  - On-body: 79.5 dB
  - Off-body: 81.5 dB
- Generally larger attenuation than non-sleeping channels

Outage probability



- Best case outage probability (attenuation > 100 dB) is more than 10% for both on-body (13.5%) and off-body (10.9%) channels

Outage duration (on-body to on-body only)



- Showing percentage of time that continuous outages of larger than *x* seconds (on horizontal axis) occur in all on-body to on-body measurements
  - Example: A receiver with a sensitivity of -88 dBm will experience outages of larger than 1000 seconds 5% of the time
- Long (duration) outages are infrequent, but because they are long, they take up a large fraction of the total time

Comments

- On-body and off-body results are very similar.
  - Attenuation effects are from the same sources
    - Shadowing from body
    - Antenna orientation
    - Distances are similar (substantially less than 3m)
  - This sort of attenuation is not frequency dependent – can not change channel within same band to avoid

- More attenuation than non-sleeping channels
- Minimum PER > 10% with -100dBm receive sensitivity
- Long outages are infrequent, but they account for a large percentage of the total time

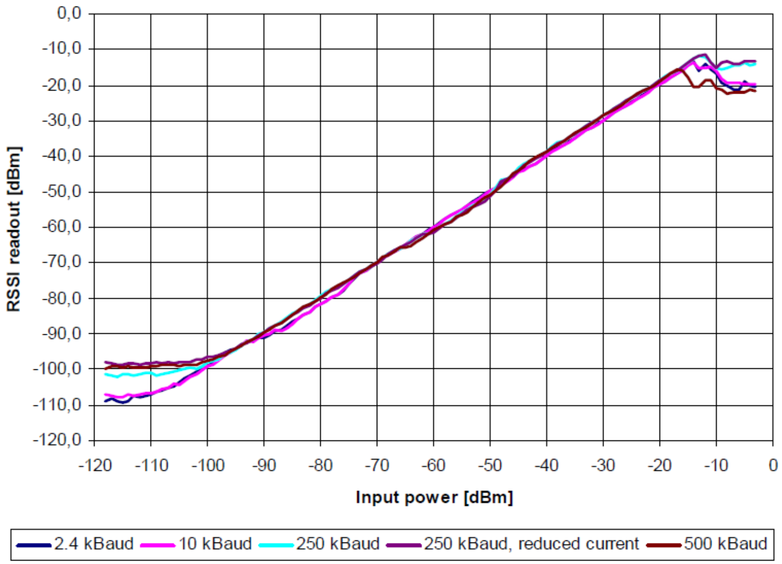
Appendix (added January 2010)

- November 2009: Concerns were raised about the validity of the sleeping channel results:
  - [a] Accuracy of RSSI estimator?
    - What sort of estimator? Is it any good?
  - [b] Does the human body adversely affect the antenna gain or its radiation pattern?
- [c] How important are these results, can't we just switch channels do avoid high attenuation from shadowing?
    - Does channel gain change with frequency?
- Follow-up measurements were performed to answer these questions

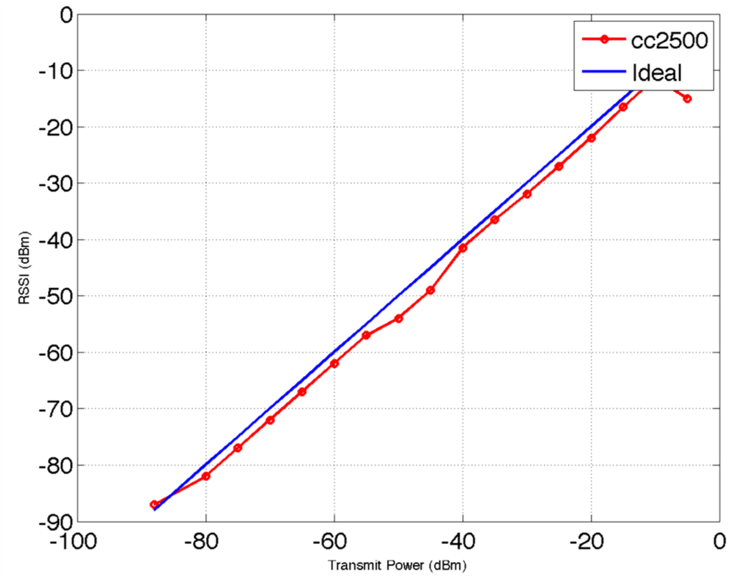
[a] RSSI estimator accuracy

- Transceiver is a Texas Instruments Chipcon cc2500
  - Digital RSSI estimation

Input power vs. Output power: (a) Datasheet



(b) Our measurement



- Measured sleeping RSSI data in range -100 to -40 dBm. RSSI estimator accurate within this range (from datasheet)
- Our measurement: Maximum error of 2 dB from ideal response

[b] Effect of human body on antenna (setup)

- Comparing free-space (no body present) and on-body measurements to determine effect of human body on antenna
  - Measured RSSI at 3 distances and 6 Rx antenna orientations
  - Body pressed against Perspex mounting for on-body (Perspex mounting approximately as thick as sensor pouch used for sleeping measurements)
- Indoor & outdoor measurements to account for possible multipath effects
  - Outdoor: Grassy field (no objects within 50m radius)
  - Indoor: Large room (much larger than typical bedroom). Ceiling >3m. Carpet floor

mount. front

mount. side

orient. flat-rot

orient. flat

orient. side-rot

orient. side

orient. up-rot

orient. up

[b] Effect of human body on antenna (results)

Channel gain (dB): (a) Indoor

Distance (m)	Tx Orient	Rx Orient	Rx Rotated	BODY		
				None	On-body	Diff
1	Upright	Upright	No	-67	-70	3
1	Upright	Upright	Yes	-71.5	-65	-6.5
1	Upright	Sideways	No	-63.5	-61.5	-2
1	Upright	Sideways	Yes	-73.5	-76.5	3
1	Upright	Flat	No	-74	-73.5	-0.5
1	Upright	Flat	Yes	-70.5	-64	-6.5
2	Upright	Upright	No	-75	-71	-4
2	Upright	Upright	Yes	-68	-70	2
2	Upright	Sideways	No	-68.5	-76.5	8
2	Upright	Sideways	Yes	-77.5	-78.5	1
2	Upright	Flat	No	-75.5	-75.5	0
2	Upright	Flat	Yes	-77.5	-71.5	-6
3	Upright	Upright	No	-84	-87	3
3	Upright	Upright	Yes	-82.5	-80	-2.5
3	Upright	Sideways	No	-73.5	-81	7.5
3	Upright	Sideways	Yes	-81.5		
3	Upright	Flat	No	-82	-82	0
3	Upright	Flat	Yes	-75.5	-69.5	-6
			Mean:	**-74.5**	**-73.7**	**-0.4**
			Median:	**-74.5**	**-73.5**	**0.0**

(b) Outdoor

Distance (m)	Tx Orient	Rx Orient	Rx Rotated	BODY		
				None	On-body	Diff
1	Upright	Upright	No	-73	-67.5	-5.5
1	Upright	Upright	Yes	-68	-65.5	-2.5
1	Upright	Sideways	No	-68.5	-71	2.5
1	Upright	Sideways	Yes	-74.5	-75	0.5
1	Upright	Flat	No	-66.5	-60.5	-6
1	Upright	Flat	Yes	-80.5	-75	-5.5
2	Upright	Upright	No	-83	-78	-5
2	Upright	Upright	Yes	-72.5	-68.5	-4
2	Upright	Sideways	No	-72.5	-77.5	5
2	Upright	Sideways	Yes	-86.5	-88.5	2
2	Upright	Flat	No	-71.5	-65.5	-6
2	Upright	Flat	Yes	-83	-79.5	-3.5
3	Upright	Upright	No		-83.5	
3	Upright	Upright	Yes	-76.5	-72.5	-4
3	Upright	Sideways	No	-76.5	-78.5	2
3	Upright	Sideways	Yes	-85	-86.5	1.5
3	Upright	Flat	No	-78	-71	-7
3	Upright	Flat	Yes	-84	-79	-5
			Mean:	**-76.5**	**-74.6**	**-2.4**
			Median:	**-76.5**	**-75.0**	**-4.0**

- Aggregating over all measurements: Difference between free space and on-body measurements is small ➔ No negative effect on RSSI from presence of human body
  - Human body seems to have a small positive(!) effect

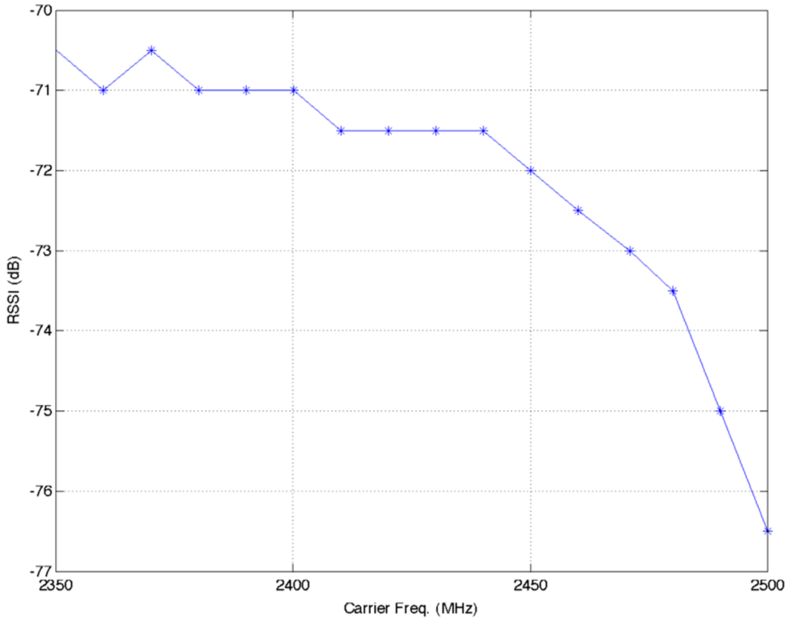
[c] Frequency diversity for sleeping (setup)

Device positions
Next to bed (head)
Hip (front)

- Posit that shadowing from human body is the major cause of the large attenuation in the sleeping-channel
- Idea: If one channel exhibits a high attenuation from shadowing, will another channel in the same band (e.g., 2.4 GHz ISM) be better?
- 2 x 2-minute experiments
  1. Tx at hip, Rx next to bed
  2. Tx and Rx swapped

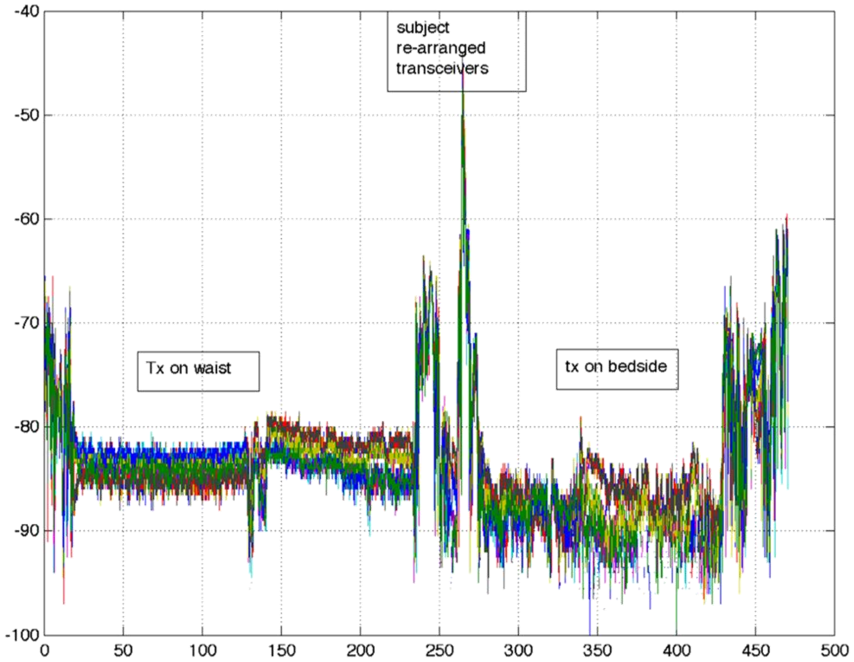
[c] Channel sounder frequency response

- Median free space frequency response of entire system
  - Antenna has a quoted range of 2400 – 2483.5 MHz
  - Measurements in following slides only go up to 2450 MHz (less than 2 dB variation in system response)
  - Sleeping measurements were performed at 2360 MHz (relative system attenuation nominally zero)



[c] Frequency diversity for sleeping (results)

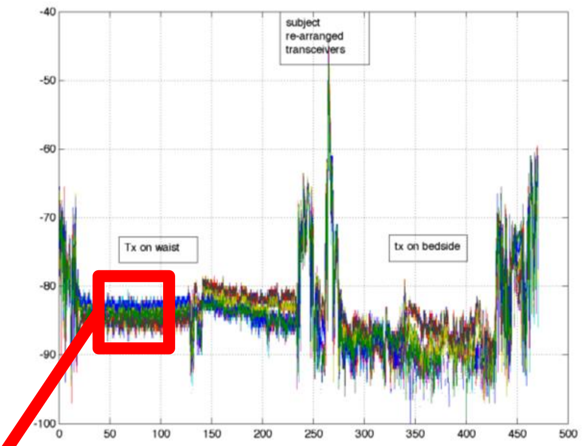
- Frequency hopping system
  - 10 ms between hops
  - Each colour represents a frequency
  - Measured channel attenuation (dBm) vs. time (seconds)
  - Frequencies = {2.35, 2.36, 2.37, 2.38, 2.39, 2.40, 2.41, 2.42, 2.43, 2.44, 2.45, 2.46, 2.471, 2.48, 2.49, 2.50} GHz
  - Avoiding n/2 crystal oscillator frequencies (as manufacturer suggests)

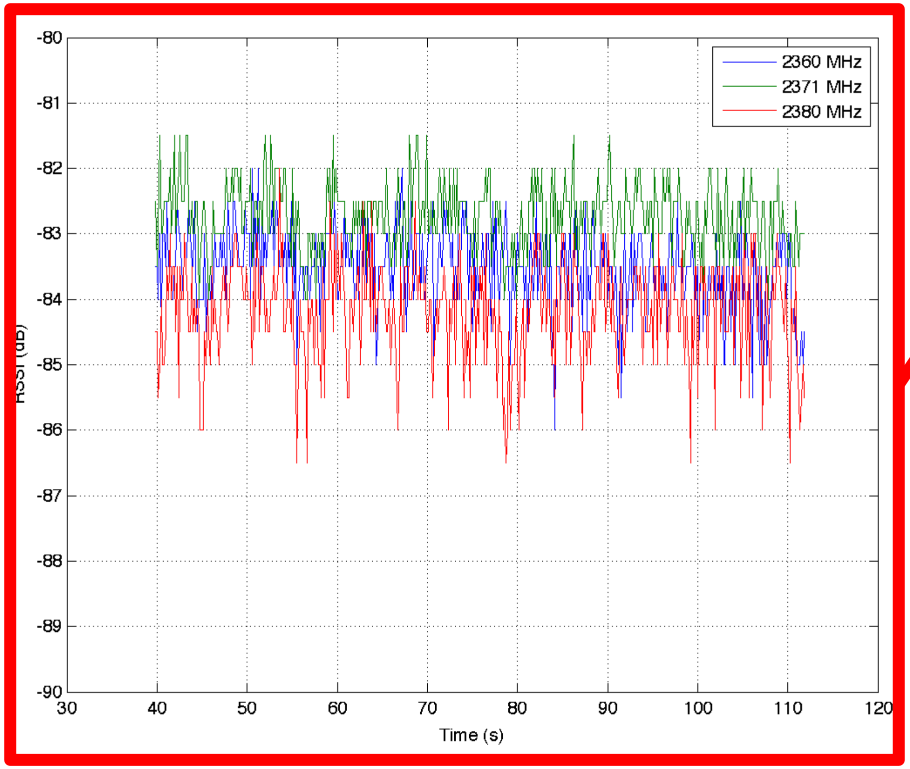


- Difference between frequencies is small (much less than measured channel variation due to shadowing)
  - Can not change to a different channel to avoid shadowing (within same frequency band)
  - Suggests that shadowing (not multipath) is dominant effect

[c] Frequency diversity for sleeping (more)

- Hip to bedside at 2360, 2371, 2380 MHz

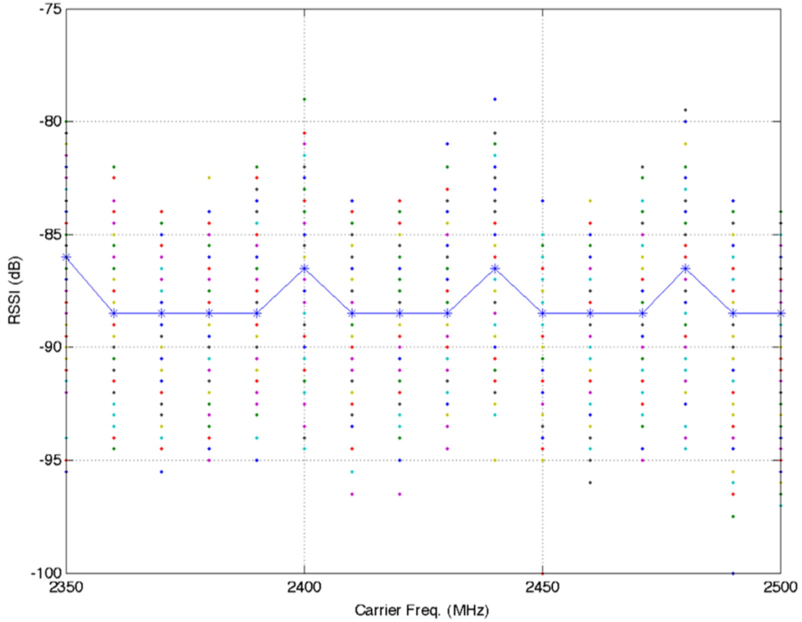




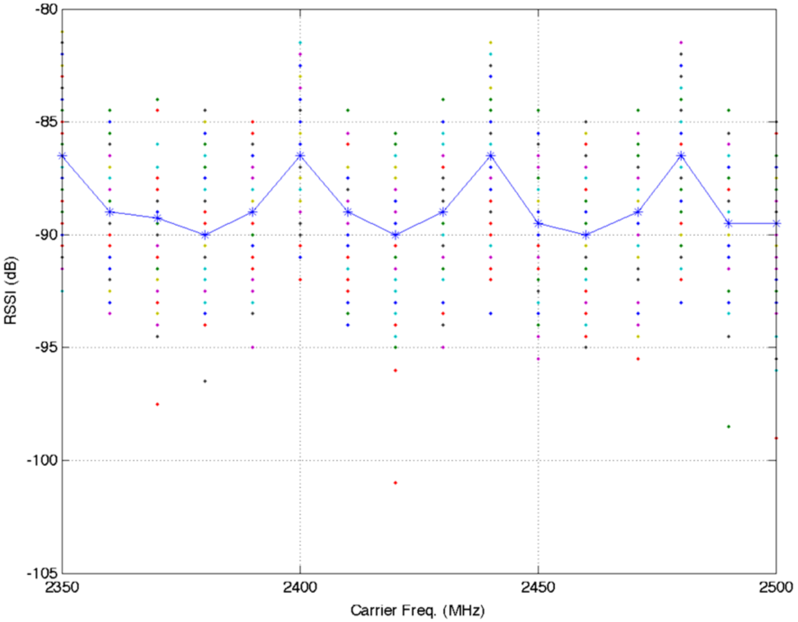
[c] Frequency diversity for sleeping (last one)

- Median RSSI as a function of carrier frequency
  - Flat frequency response

Median RSSI (dBm): (a) Hip to bedside



(b) Ankle to bedside



Comments

- [a] RSSI estimator seems accurate
  - Over frequency and input signal level
- [b] Human body does not have a negative effect on system gain
- [c] Can not find a channel in the same band that will have (significantly) lower attenuation from shadowing
  - Can not swap channels to avoid nulls

- We believe that the sleeping channel measurements are valid