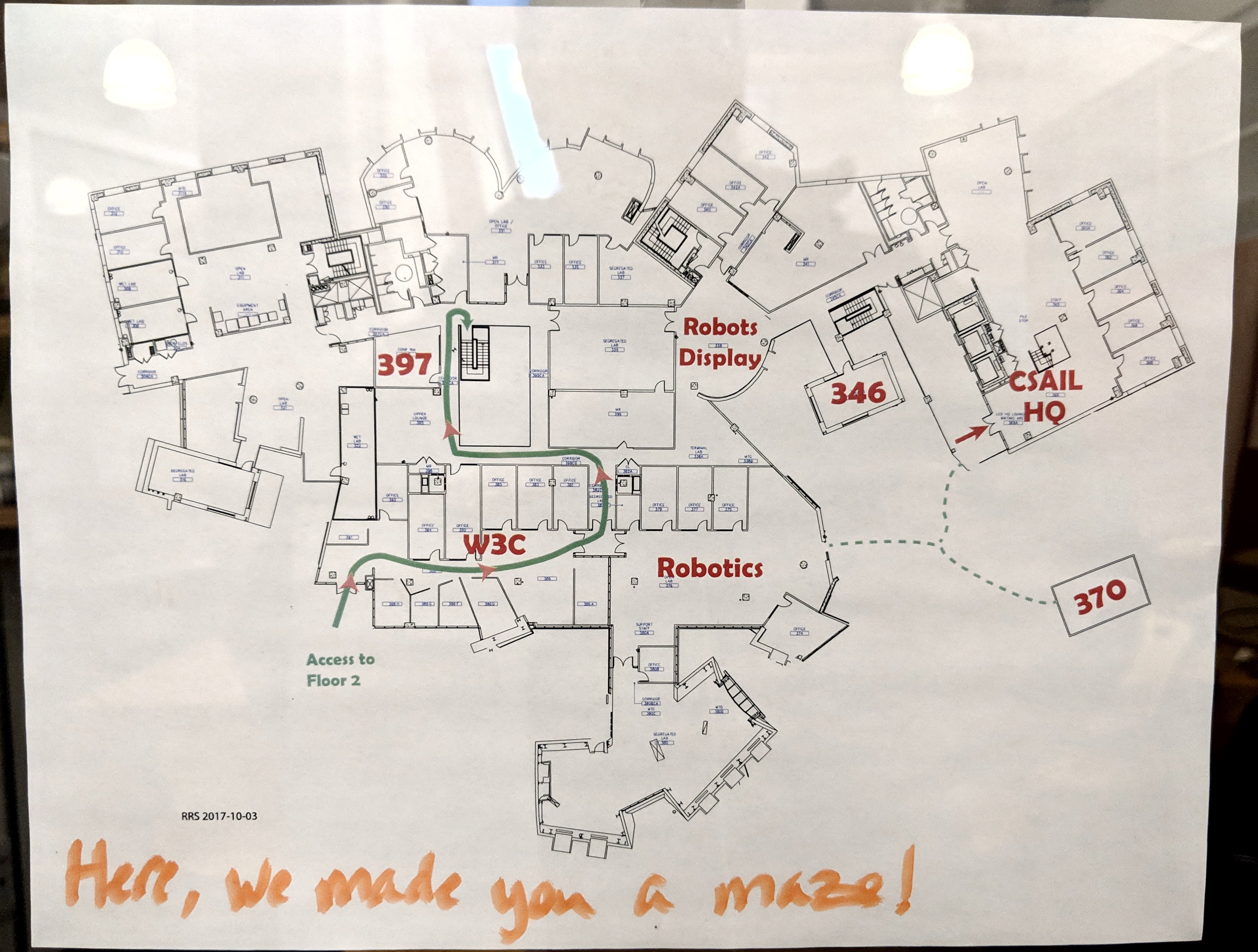
Indoor navigation using WiFi round-trip time

Berthold K.P. Horn

- Fine Time Measurement (FTM) Round Trip Time (RTT)
- IEEE 802.11mc
- Background: Timing Advance (TA) in GSM and LTE
- Recovering initiator position from distances to responders
- Dilution of Precision (DOP) — a.k.a. Noise Gain
- Non-Gaussian, non-stationary measurement error
- Best spatial arrangement for responders
- Some issues, problems, and currrent limitations
- When will it happen?


397
Robots Display
346
CSAIL HQ
W3C
Robotics
370
Access to Floor 2
RRS 2017-10-03
Here, we made you a maze!

What’s is indoor location good for?

- **Navigation:** Turn-by-turn wayfinding. Show me the way to the meeting.
- **Asset Management:** Where is the fork-lift? wheel-chair? ultra-sound machine?
- **Geo-fencing:** Animal tagging. Child safety. Disable company laptops.
- **Location based marketing:** Alert consumer to nearby item or trigger coupon.
- **Emergency Services:** Locate situation within building. Civic address and floor.
- **Internet of Things:** Dim the light in the room I am in. Lock the correct door.
- **Warehousing and robotics:** Guide autonomous forklifts.
- **Network management:** Pinpoint equipment failures and activate replacements.
- **Smart cities:** Public parking structures, street lighting, security cameras.
- . . .

Background: Timing Advance in cellular networks

- Timing Advance in GSM
- Timing Advance in LTE

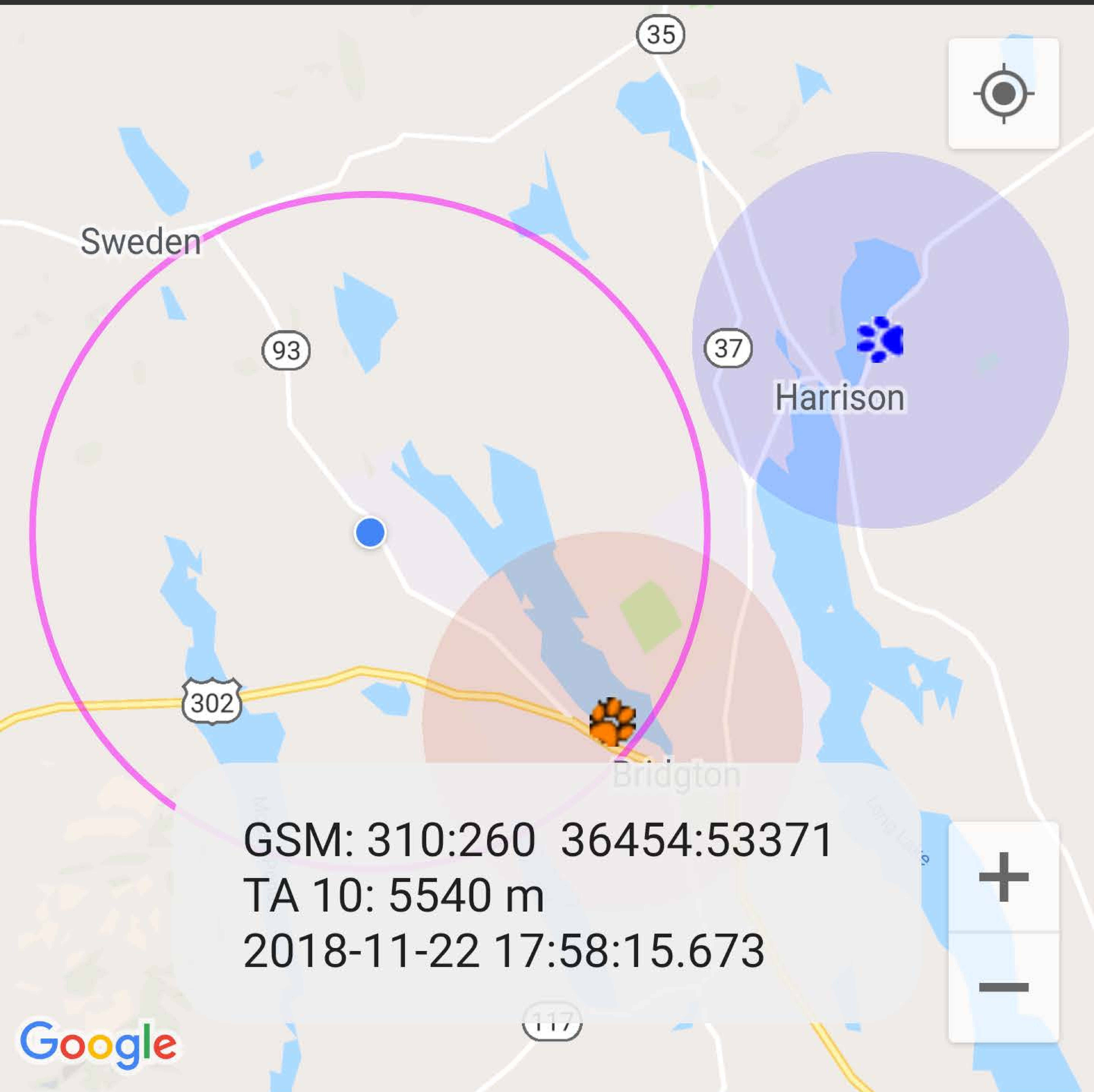
  Both use time-division duplex (TDD)

  Unlike CDMA which uses code-division duplex (CDD)

17:58 80%

CellTracker

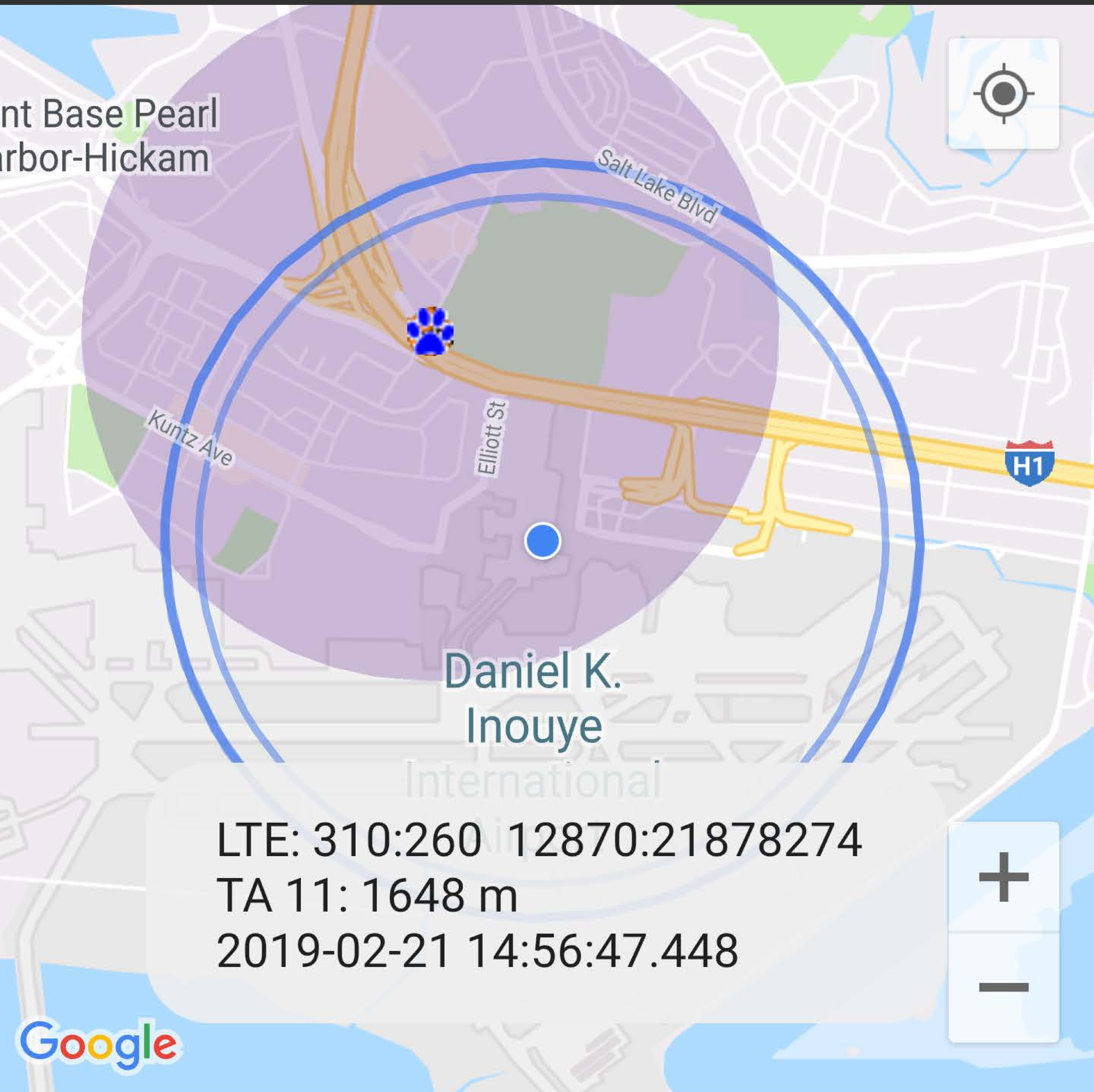
GSM 310:260 36454:53371 (0xD07B) SW   (39) |
GSM dBm -103 BER 0 -
GSM ARFCN 605 BSIC 55 TA * EDGE 00 00 00 00
GPS 44.09028 -70.77584 alt 186 |
acc 28 vel 0.0 azi   -1 Sat 15/18 \
BASE N/A |
GSM 44.06219 -70.72611 s 3133 R I
LTE (no registered cells)
IP 192.168.1.13 45.46.100.69 \
BAT 80% 3.999 V 27 C (SIM: T-Mobile) -
2G 310:410 /
2G EDGE /
3 AP max -47 a8:9a:93:91:04:3e



14:56 79° LTE 68%

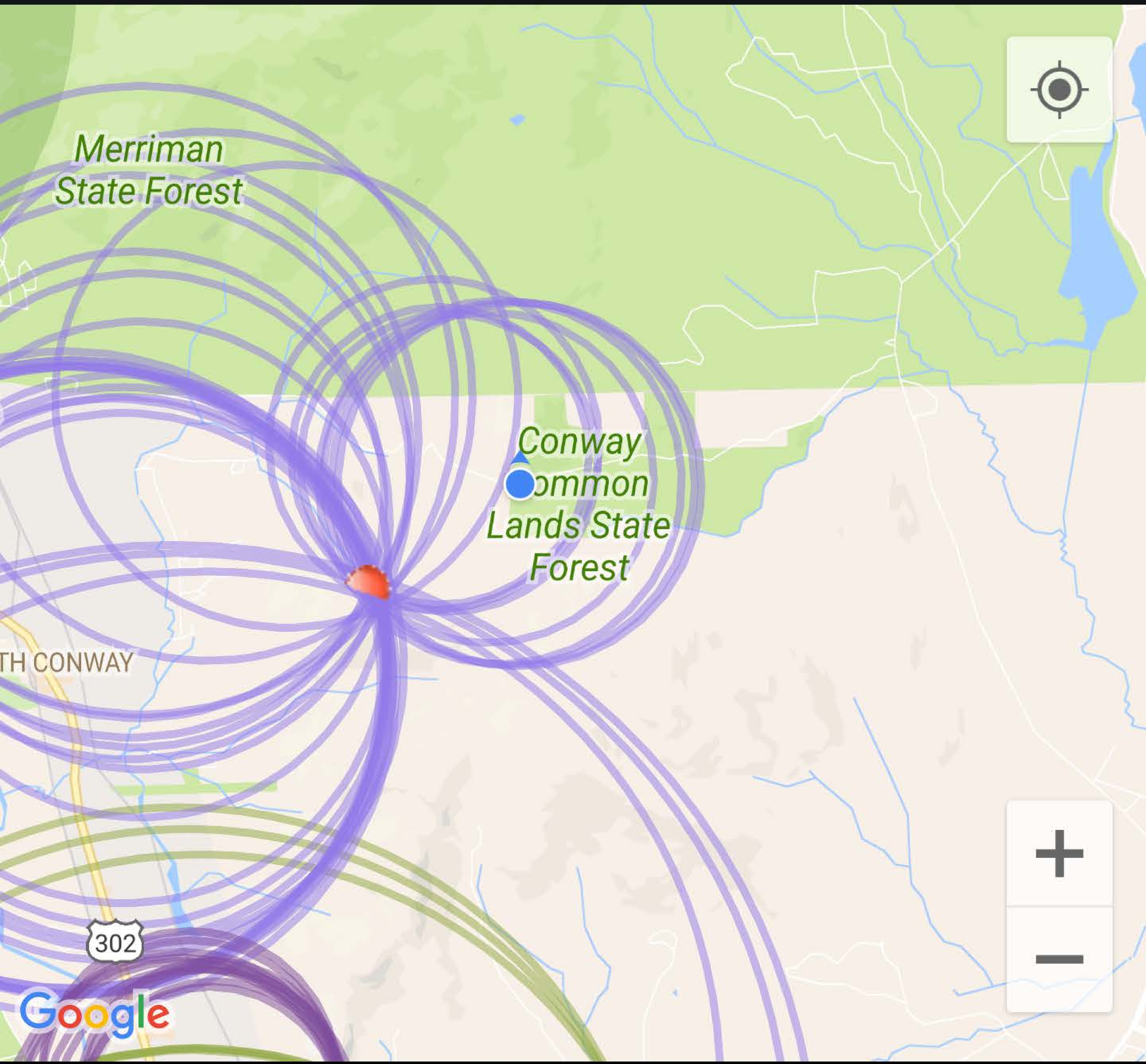
CellTracker

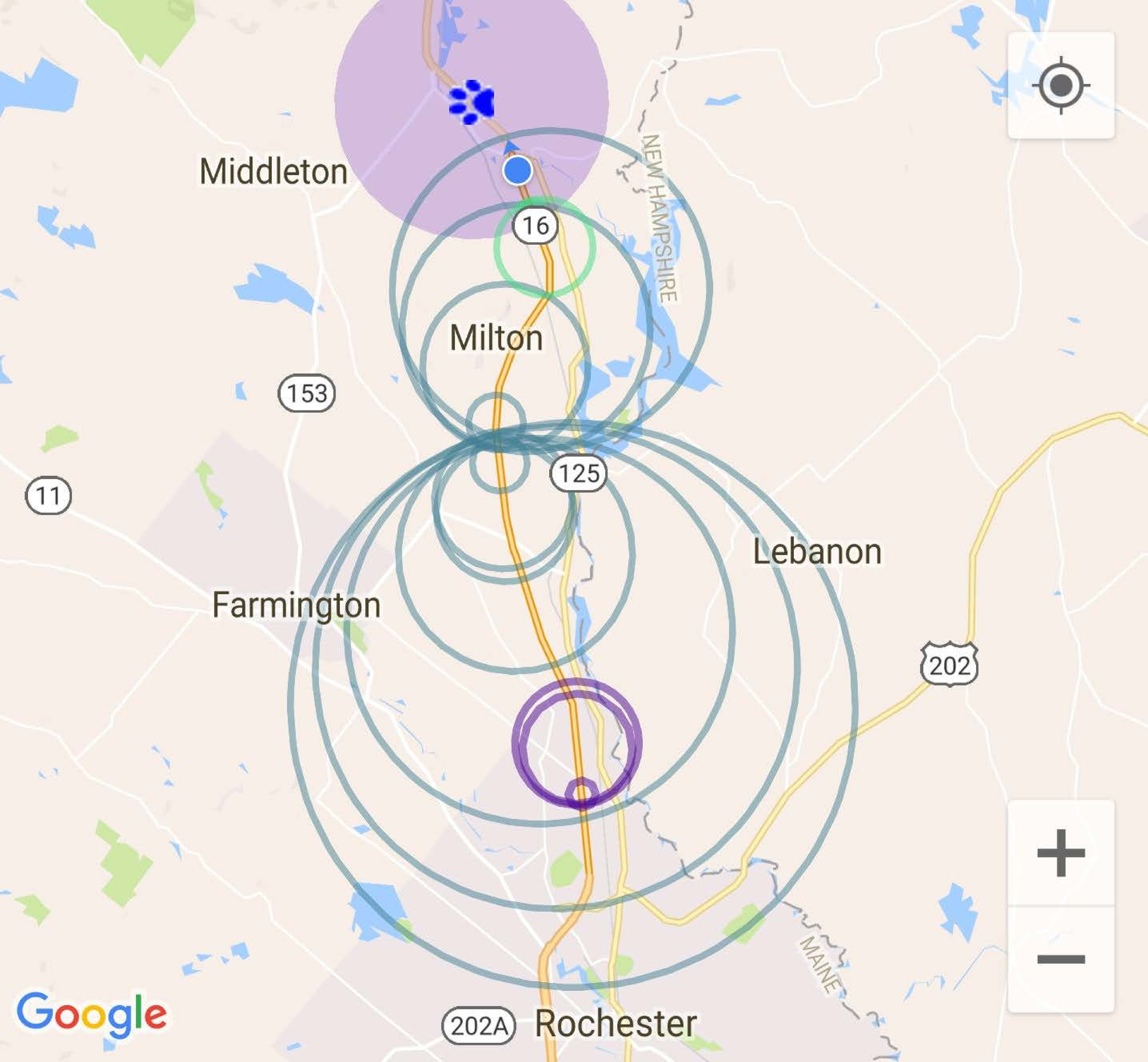
```
VoLTE 310:260 12870:21878274 (0x14DD602) NW
VoLTE voice connection (GSM) \
LTE EARFCN 2250 TA  * LTE 00 00 00 12 \
GPS  21.33276 -157.92477 alt 9 /
acc  17 vel 0.0 azi   -1 Sat 0/22 |
BASE N/A \
GSM  21.34093 -157.92948 s 1523 R L 0:0 /
LTE  21.34093 -157.92948 s 1523 R I
IP 192.0.0.4 136.22.79.149 -
BAT 68% 3.93 V 37 C  (SIM: T-Mobile) -
LTE 310:260 12870:21878274 (0x14DD602) 90 \
LTE SS 19 RP -103 RQ -11 SN  30.0 CQ * (S)  -
Device DOES support WIFI RTT
```



14:12

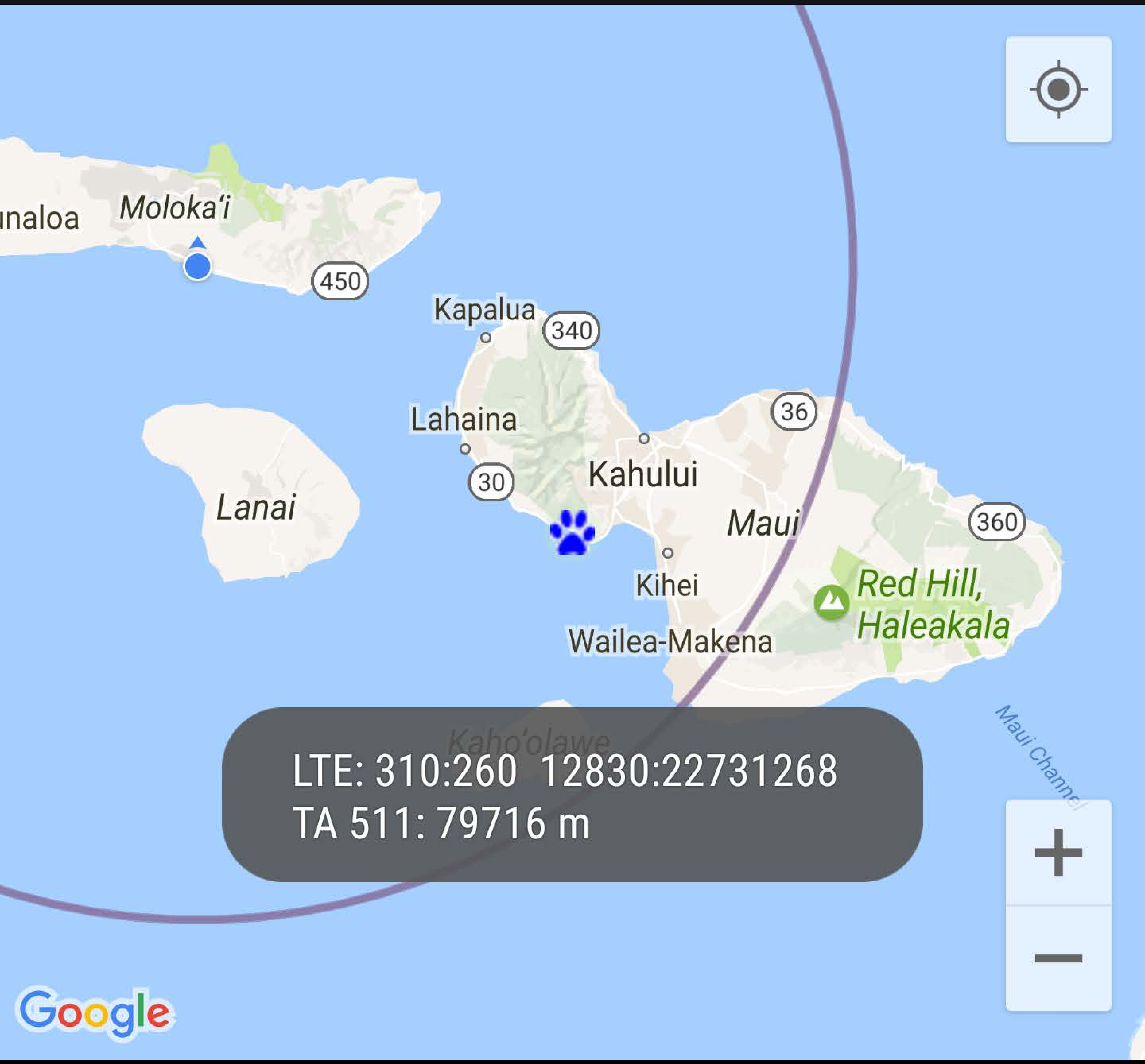
CDMA 445:16:19681 (0x4CE1) SW L (1198) \
CDMA dBm -91 EcIo -7 |
LTE EARFCN 5090 LTE 00 00 00 11 /
FUSED 44.06815 -71.07408 h 471 /
acc   7 vel 0.00 azi   0 Sat 12/18 -
BASE 44.05944 -71.09111 d 1672 SW \
MMAP 44.10829 -71.16970 s 3614 |
IP 10.200.221.181 166.182.80.117 \
BAT 57% 3.856 V 32 C Li-ion |
LTE 311:580 2822:84515841 (0x5099C01) 81 /
LTE SS 8 RP -128 RQ -15 SN -3.4 CQ * (S) /

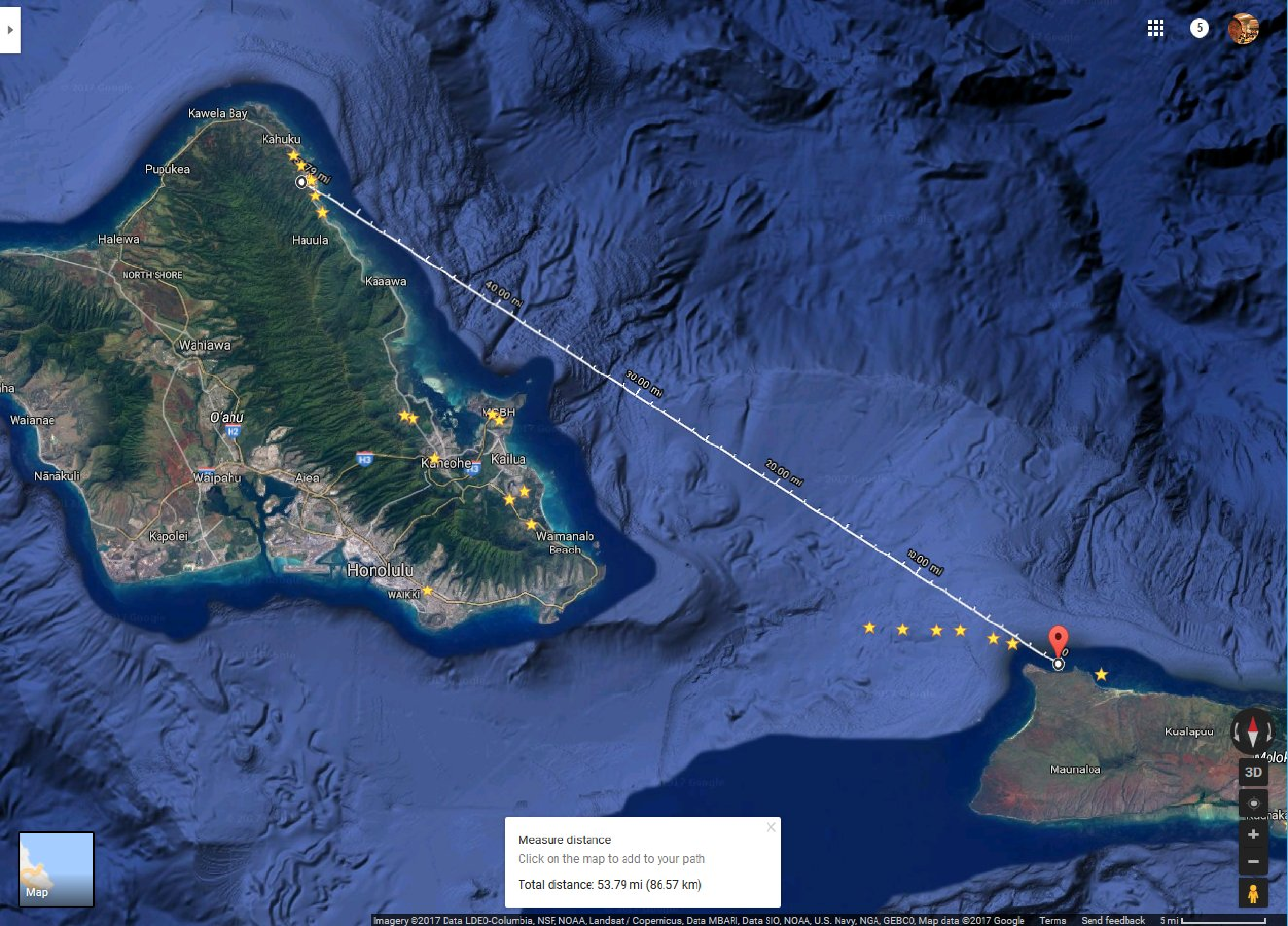



Middleton
16
NEW HAMPSHIRE
Milton
153
125
11
Lebanon
Farmington
202
MAINE
202A
Rochester
Google

73° 21:51

GSM 310:260 19298:16247450:3 (0xF7EA9A)
GSM N/A \
LTE EARFCN 5035 LTE 00 00 00 01 /
FUSED 21.07841 -156.99653 h 23 -
acc 3 vel 0.00 azi 0 -
MCC:MNC 310:260 Fi Network |
MMAP 20.78655 -156.55677 s 3565 |
IP 192.0.0.4 75.85.137.247 |
BAT 40% 3.693 V 36.7 C Li-ion -
LTE 310:260 12830:22731268 (0x15ADA04) 428 |
LTE SS 12 RP -116 RQ -12 SN 30.0 CQ * (S) |




Kawela Bay
Kahuku
Pupukea
Haleiwa
Hauula
NORTH SHORE
Kaaawa
40.00 mi
Wahiawa
30.00 mi
Waianae
O'ahu
MCBH
Kaneohe
Kailua
Nānākuli
Waipahu
Aiea
20.00 mi
Kapolei
Waimanalo
Beach
10.00 mi
Honolulu
WAIKIKI
Kualapuu
Maunaloa
3D
Map
Measure distance
Click on the map to add to your path
Total distance: 53.79 mi (86.57 km)
Imagery ©2017 Data LDEO-Columbia, NSF, NOAA, Landsat / Copernicus, Data MBARI, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Map data ©2017 Google
Terms
Send feedback
5 mi

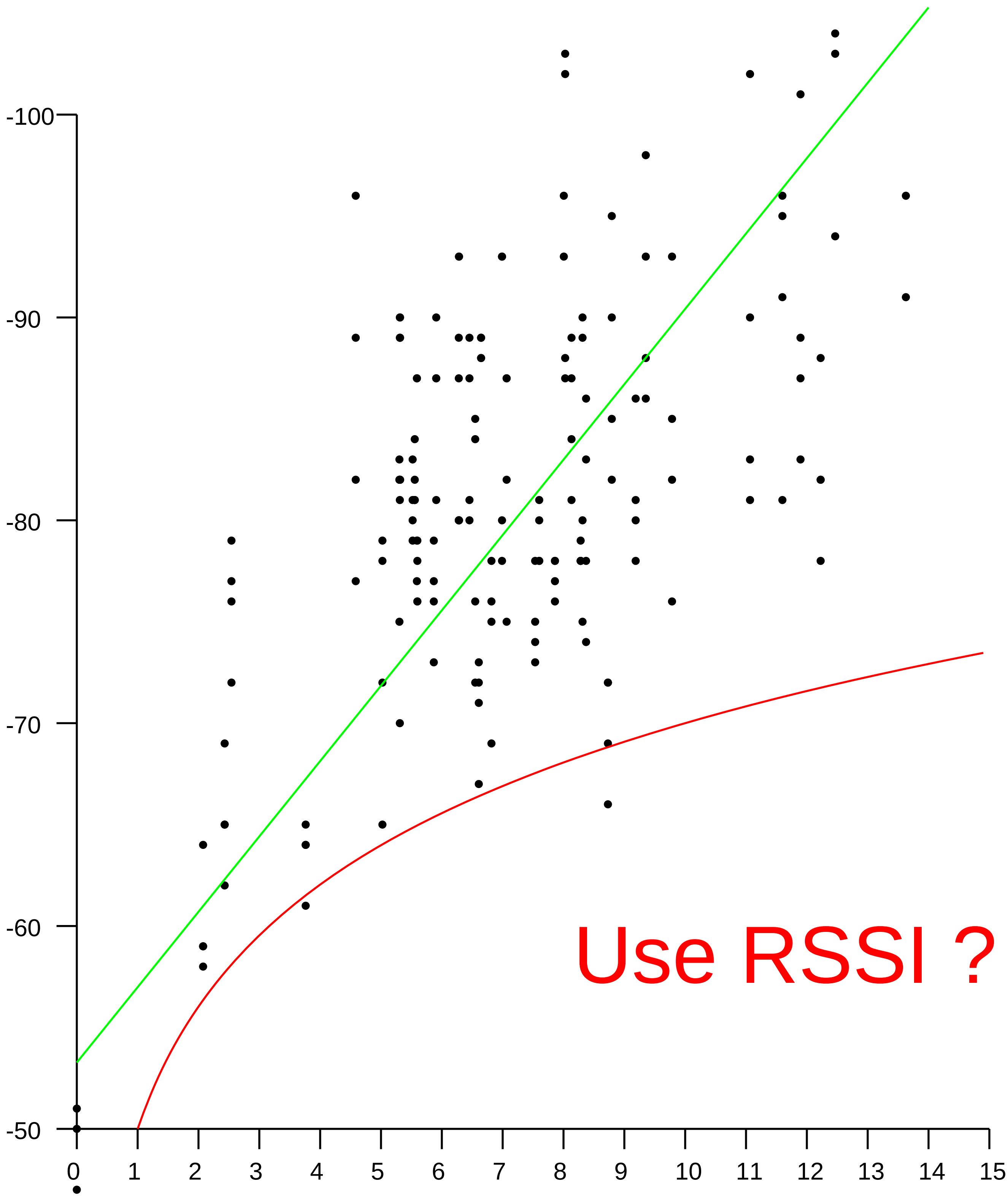
Background: using Received Signal Strength:

- Estimate distance based on RSSI (dBm)

  Does signal strength obey the inverse square law?

- “Fingerprinting” a venue

  Tedious. Repeat when access point configuration changes



Horizontal axis: actual distance (meter)

Vertical axis: signal strength (dBm)

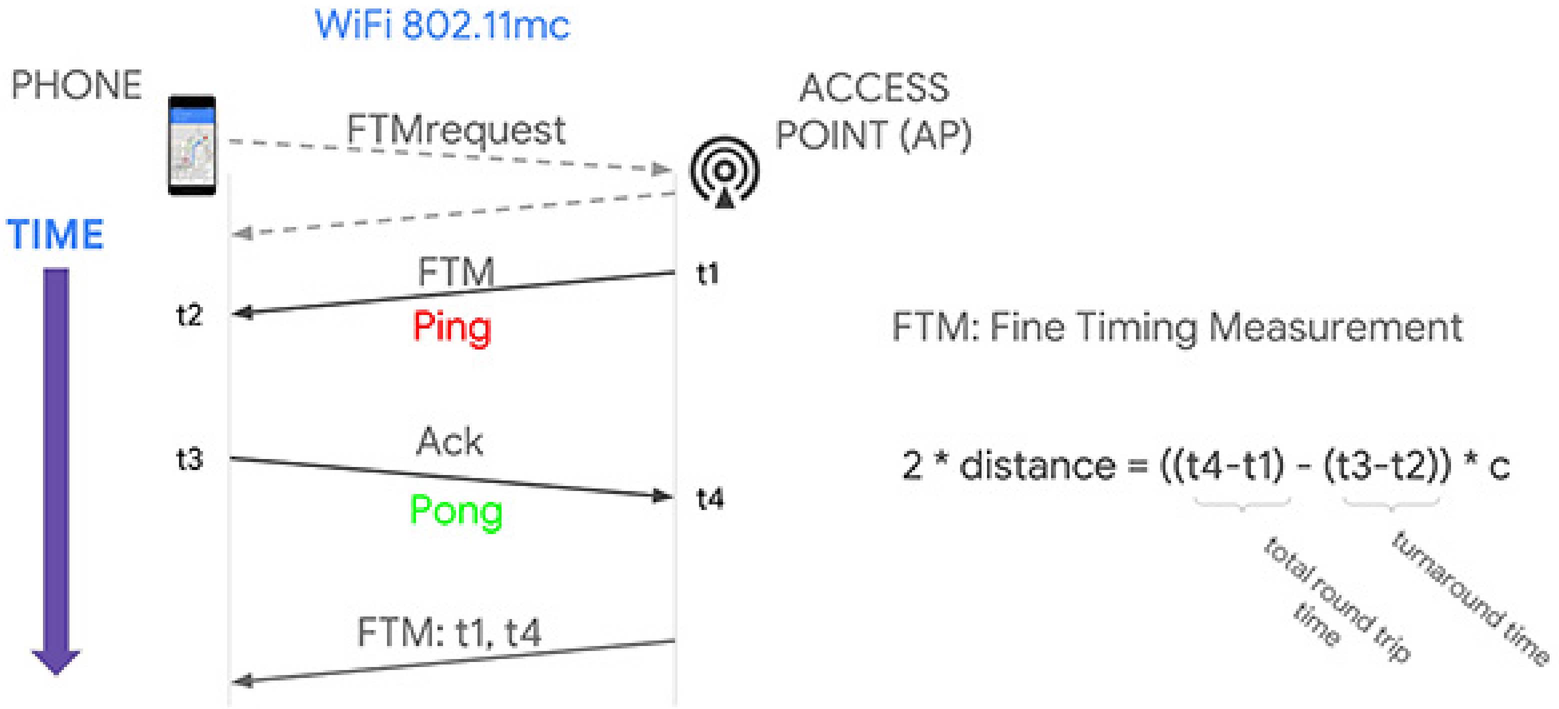
Green line: linear fit -53 - 3.7 * R dBm

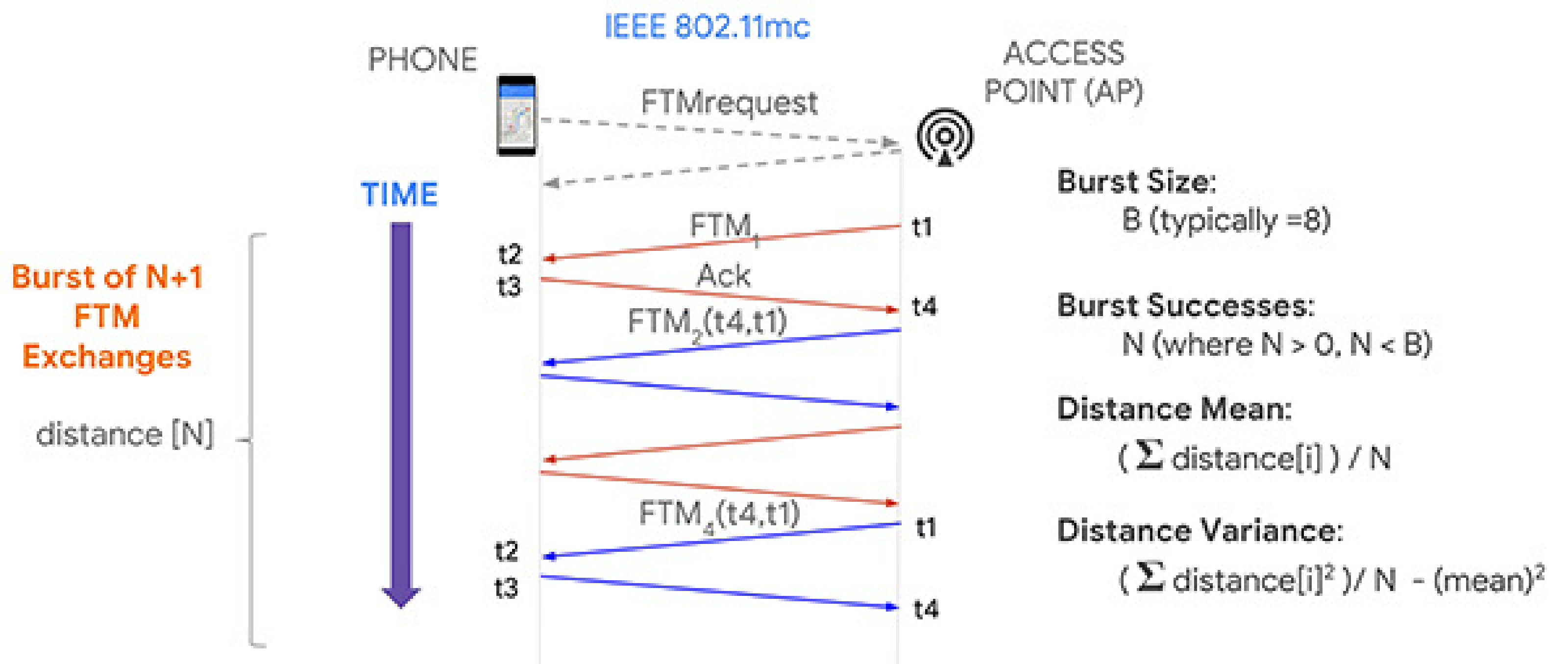
Red curve: expected -50 - 20 * log(R) dBm

802.11mc

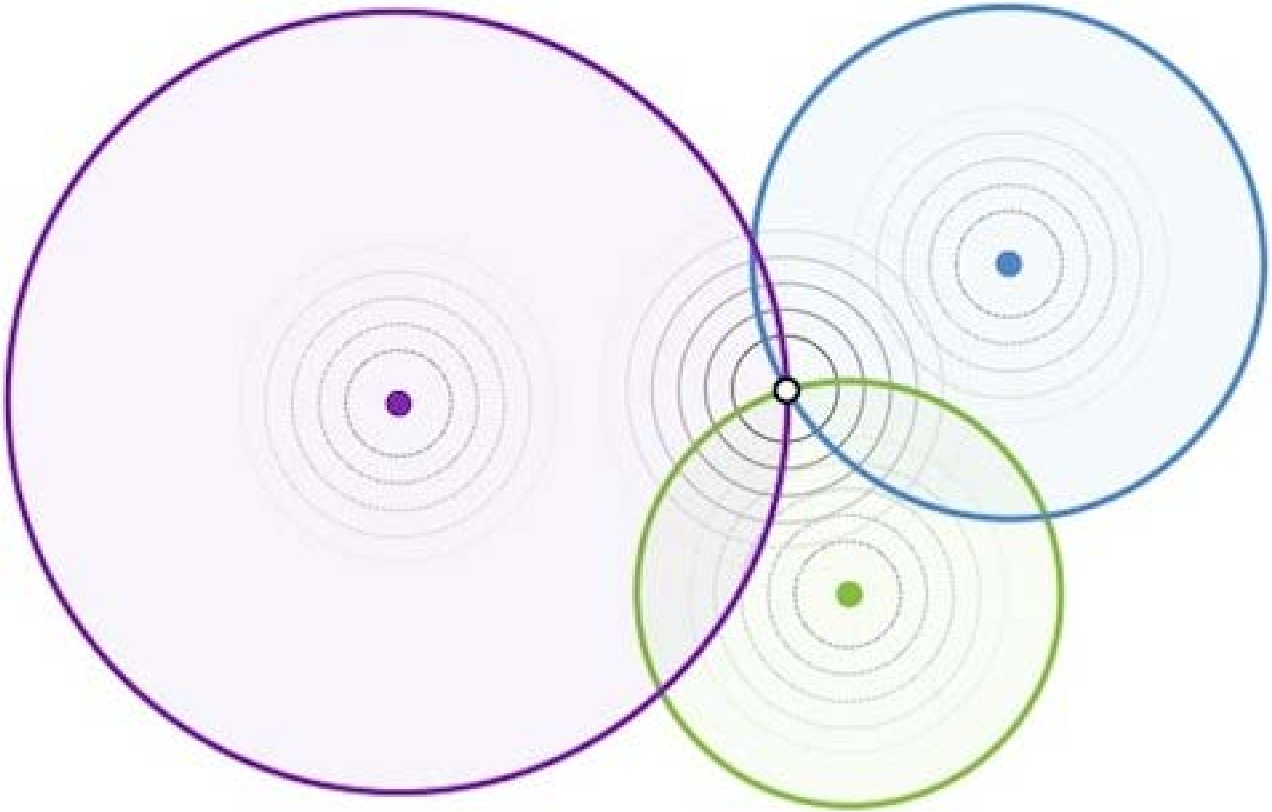
- Fine Time Measurement (FTM)

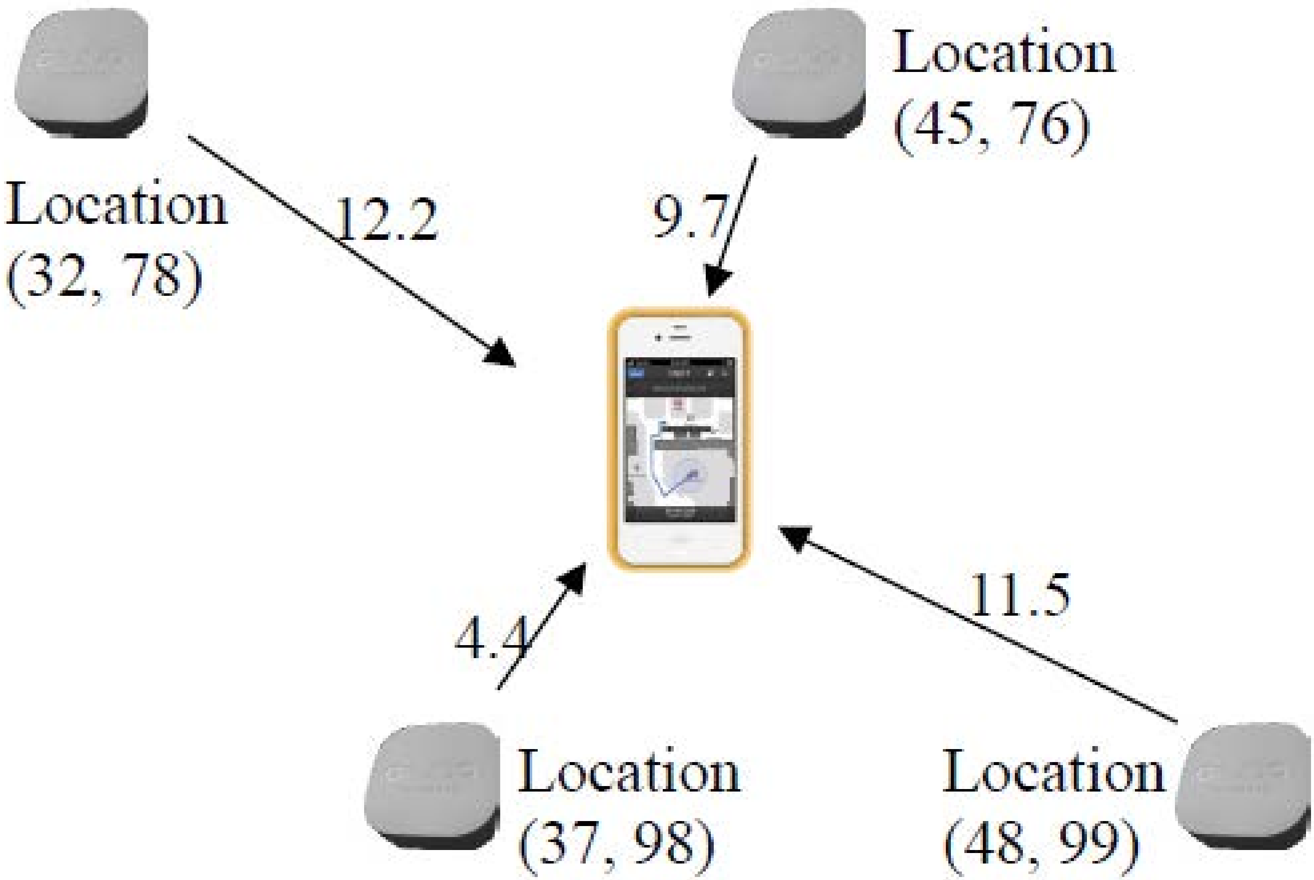
- Round Trip Time (RTT)


WiFi 802.11mc
PHONE
ACCESS POINT (AP)
TIME
FTMrequest
FTM
t1
t2
Ping
Ack
t3
t4
Pong
FTM: t1, t4
FTM: Fine Timing Measurement
2 * distance = ((t4-t1) - (t3-t2)) * c
total round trip time
turnaround time



IEEE 802.11mc
PHONE
ACCESS POINT (AP)
FTMrequest
TIME
FTM1
t1
t2
Ack
t3
t4
FTM2(t4,t1)
Burst of N+1 FTM Exchanges
distance [N]
FTM4(t4,t1)
t1
t2
t3
t4
Burst Size:
B (typically =8)
Burst Successes:
N (where N > 0, N < B)
Distance Mean:
(Σ distance[i]) / N
Distance Variance:
(Σ distance[i]²)/ N - (mean)²





<u>Clients range relative to APs/beacons</u>

But how does that relate to ‘location’?

- Requires knowledge of AP locations
- Requires a map with frame of reference

WiFi Indoor Location Device

WiLD

Android RTT FTM (API Level 28)

get permissions: `ACCESS_FINE_LOCATION`, `CHANGE_WIFI_STATE`

register `BroadcastReceiver` for: `SCAN_RESULTS_AVAILABLE`

Call `WifiManager.ScanStart(...)` †

 receive `ScanResults` in `BroadCastReceiver`

 create `RangingRequest` from `ScanResults`

Call `WifiRttManager.startRanging(...)` ‡

`RangingResultsCallBack` `onRangingResults`

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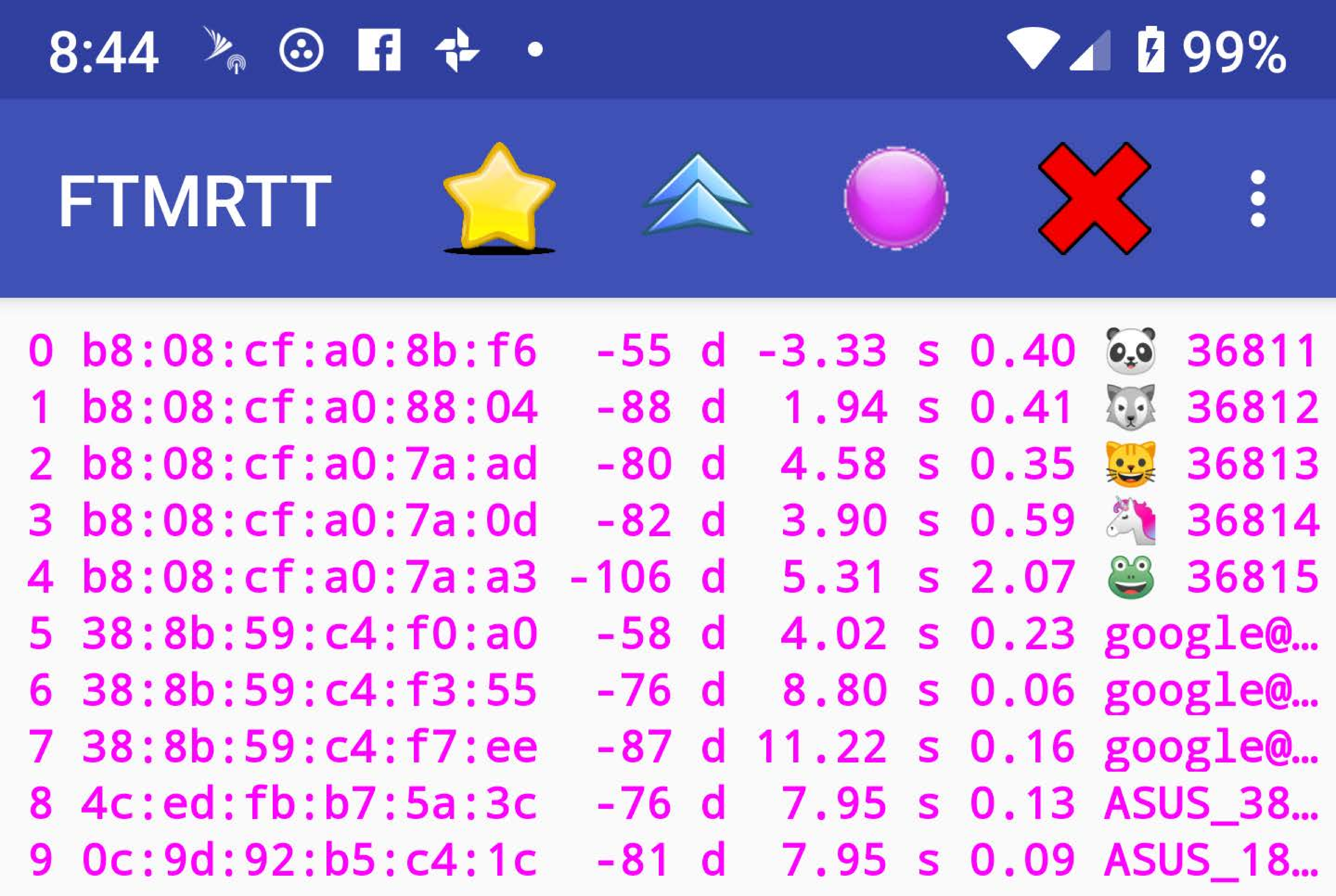
† Throttled to 4 calls per 2 minutes (and “grey listed”)

‡ Disabled when app is in background


8:44
99%
FTMRTT
0 b8:08:cf:a0:8b:f6 -55 d -3.33 s 0.40 36811
1 b8:08:cf:a0:88:04 -88 d 1.94 s 0.41 36812
2 b8:08:cf:a0:7a:ad -80 d 4.58 s 0.35 36813
3 b8:08:cf:a0:7a:0d -82 d 3.90 s 0.59 36814
4 b8:08:cf:a0:7a:a3 -106 d 5.31 s 2.07 36815
5 38:8b:59:c4:f0:a0 -58 d 4.02 s 0.23 google@…
6 38:8b:59:c4:f3:55 -76 d 8.80 s 0.06 google@…
7 38:8b:59:c4:f7:ee -87 d 11.22 s 0.16 google@…
8 4c:ed:fb:b7:5a:3c -76 d 7.95 s 0.13 ASUS_38…
9 0c:9d:92:b5:c4:1c -81 d 7.95 s 0.09 ASUS_18…

Java™

1:19 76%

Sun, Nov 4

FTMRTT • 10 RTT responses from 16 APs

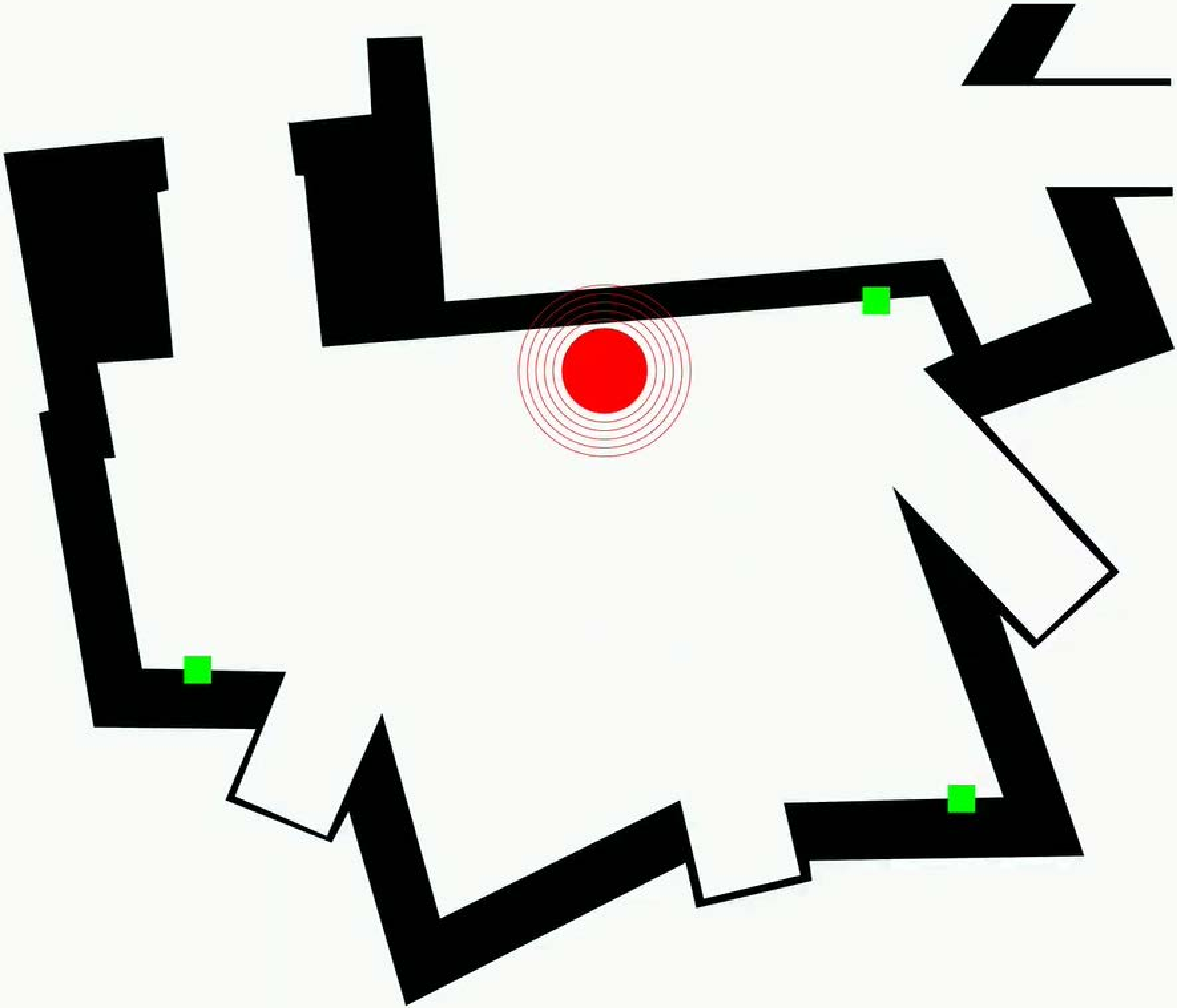
0 dBm: -56 dis: 3.03 s: 0.24 "ASUS_38_5G"
1 dBm: -85 dis: 5.34 s: 0.20 "ASUS_18_5G"
2 dBm: -77 dis: 5.87 s: 0.42 "google@176"
3 dBm: -73 dis: 2.12 s: 0.28 "😺 36813"
4 dBm: -88 dis: -0.53 s: 0.57 "🦄 36814"
5 dBm: -91 dis: 8.17 s: 0.95 "🐸 36815"
6 dBm: -89 dis: 10.95 s: 1.10 "google@176"
7 dBm: -91 dis: 12.97 s: 0.28 "google@176"
8 dBm: -92 dis: 6.22 s: 1.60 "🐼 36811"
9 dBm: -102 dis: 2.95 s: 4.71 "🐺 36812"

Signal Spy

Mobile Network: US Cellular LTE - Band 5 (85..
Connected to WIFI (google@176)

WiFi Guard • 4d

{0c:9d:



Solution Methods

$$\|\mathbf{s} - \mathbf{r}_i\| = d_i \quad \text{for} \quad i = 1, 2, \ldots n$$

$\mathbf{s}$ is the unknown position of the initiator, and
d_i is the measured distance to the responder at $\mathbf{r}_i$.

- Intersecting spheres (or circles)
- Reduction to linear equations & pseudo inverse
- Least squares & gradient descent
- Brute force grid search
- Extended Kalman filter — linearization & assumption
- Bayesian grid — transition & observation models

Reduction to Linear Equations

$$\|\mathbf{s} - \mathbf{r}_i\| = d_i$$

$$(\mathbf{s} - \mathbf{r}_i) \cdot (\mathbf{s} - \mathbf{r}_i) = d_i^2$$

$$\|\mathbf{s}\|^2 - 2\ \mathbf{r}_i \cdot \mathbf{s} + \|\mathbf{r}_i\|^2 = d_i^2$$

So we have n second order equations in **s**.
Subtract pairwise to obtain $m = n(n-1)/2$ linear equations:

$$(\mathbf{r}_j - \mathbf{r}_i) \cdot \mathbf{s} = \big((d_i^2 - d_j^2) - (R_i^2 - R_j^2)\big)/2$$

where $R_i = \|\mathbf{r}_i\|$. We can rewrite this in matrix-vector form:

$$A\mathbf{s} = \mathbf{t}$$

For $n = 3$ we get three *linearly dependent* equations.
For $n > 3$ can obtain least squares solution:

$$\mathbf{s} = (A^T A)^{-1} A^T \mathbf{t}$$

Reduction to Linear Equations

$$\|\mathbf{s} - \mathbf{r}_i\| = d_i$$

$$(\mathbf{s} - \mathbf{r}_i) \cdot (\mathbf{s} - \mathbf{r}_i) = d_i^2$$

$$\|\mathbf{s}\|^2 - 2\ \mathbf{r}_i \cdot \mathbf{s} + \|\mathbf{r}_i\|^2 = d_i^2$$

So we have n second order equations in $\mathbf{s}$.
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$$A\mathbf{s} = \mathbf{t}$$

For $n = 3$ we get three *linearly dependent* equations.
For $n > 3$ can obtain least squares solution:

$$\mathbf{s} = (A^T A)^{-1} A^T \mathbf{t}$$

BUT: Huge noise gain!

Least Squares and Gradient Descent

Find $\mathbf{s}$ that minimizes sum of squares of errors

$$e = \sum_{i=1}^{n} \left(\|\mathbf{s} - \mathbf{r}_i\| - d_i \right)^2$$

Determine the gradient

$$\nabla(e) = 2 \sum_{i=1}^{n} \left(\|\mathbf{s} - \mathbf{r}_i\| - d_i \right) \frac{\mathbf{s} - \mathbf{r}_i}{\|\mathbf{s} - \mathbf{r}_i\|}$$

Go downhill

$$\mathbf{r}^{(n+1)} = \mathbf{r}^{(n)} - \gamma \nabla(e)$$

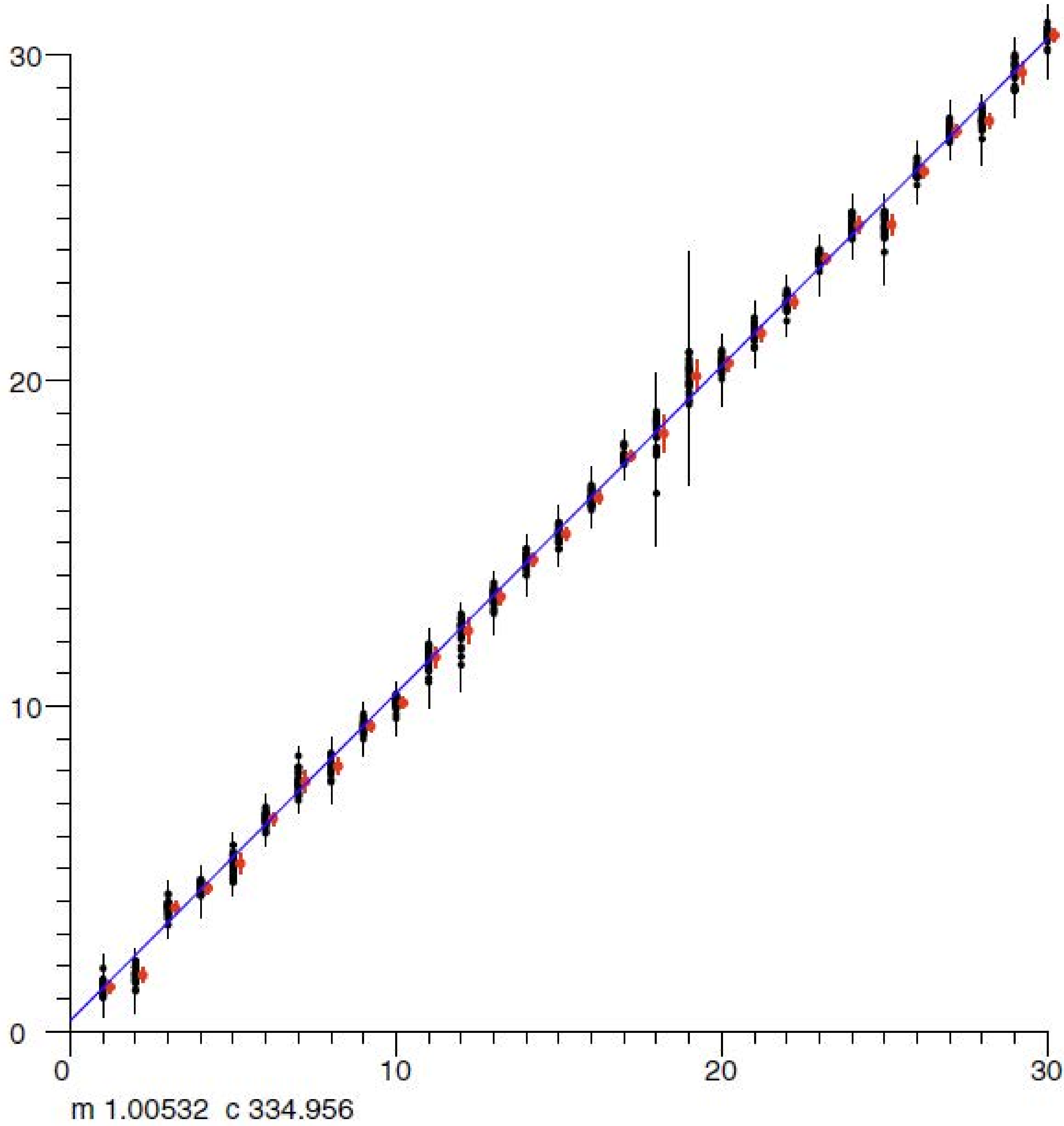
Perhaps better yet, use Newton-Raphson

$$\mathbf{r}^{(n+1)} = \mathbf{r}^{(n)} - H(e)^{-1} \nabla(e)$$

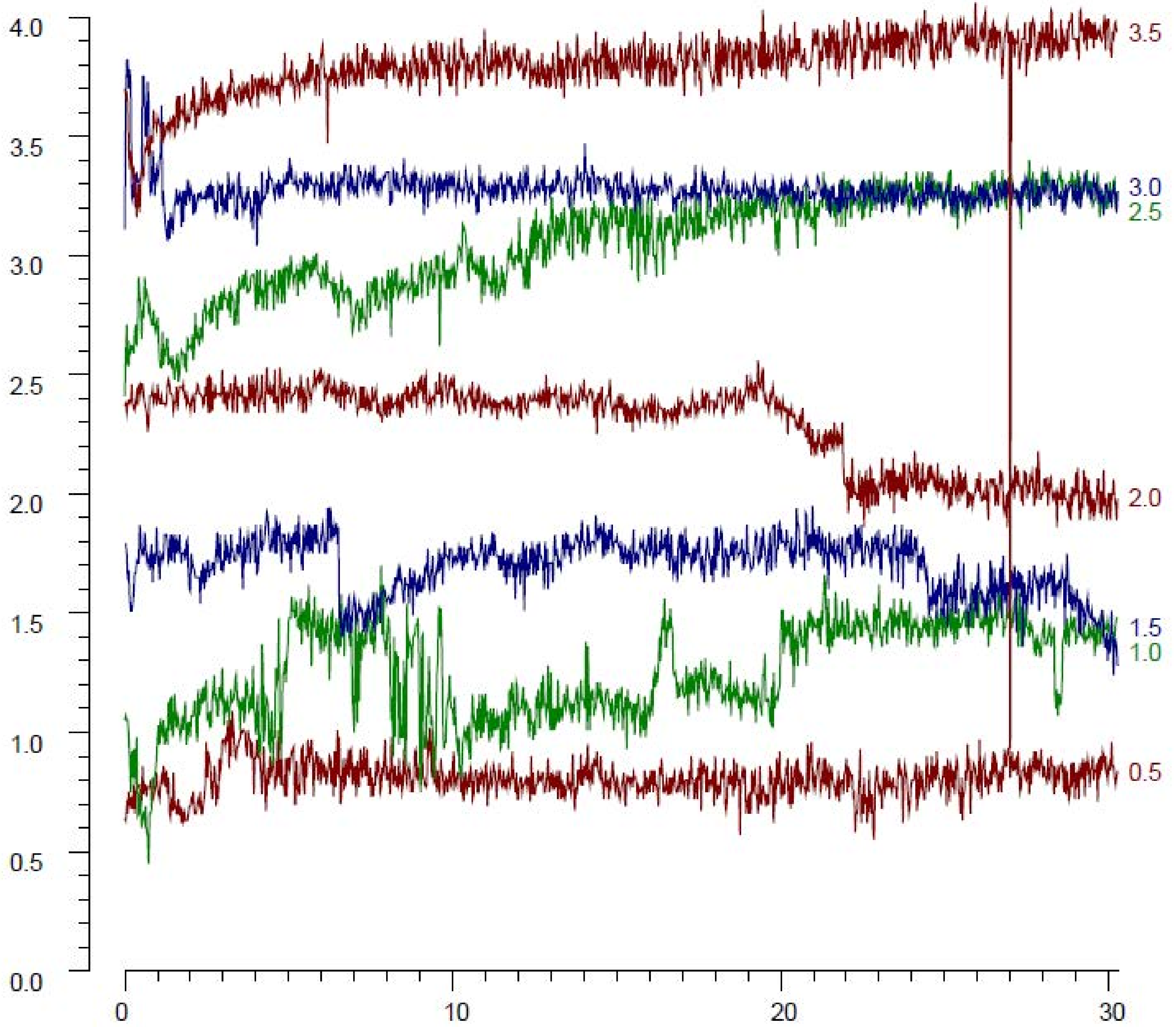
where $H(e)$ is the Hessian matrix of second partial derivatives.

Nature of the measurement "noise"

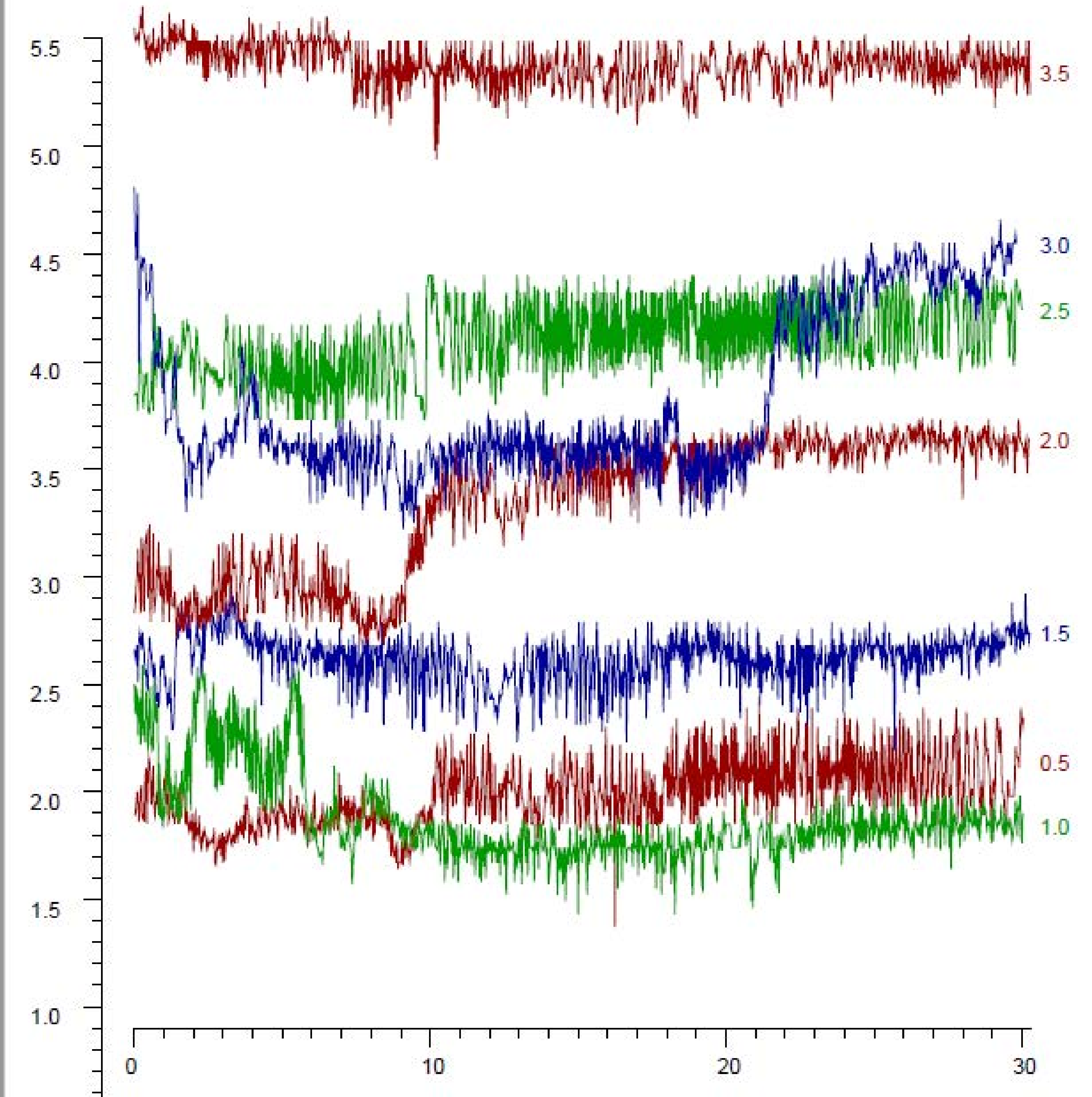
- Non-Gaussian
- Not "stationary"
- Unknown effects of the environment



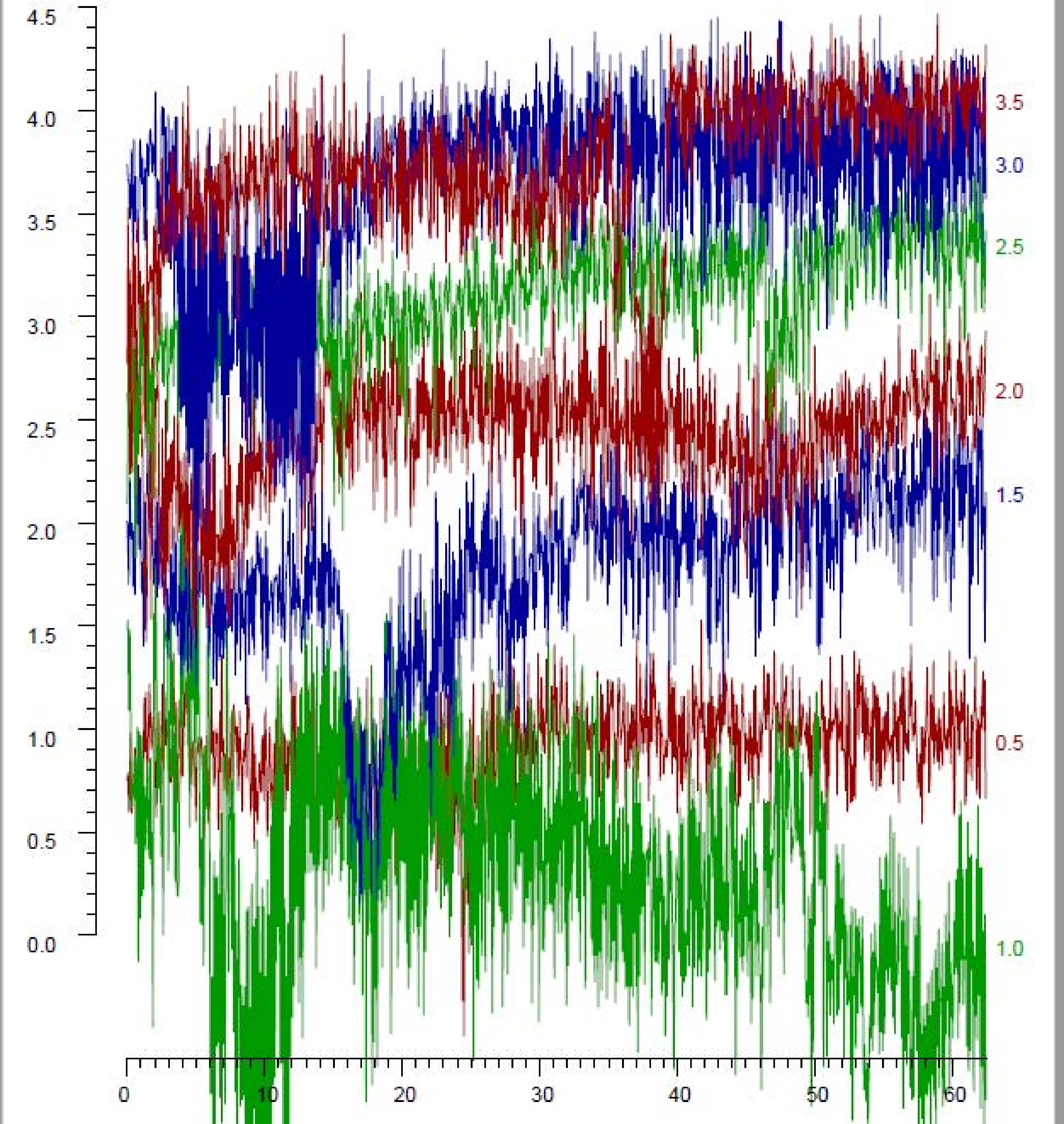
30
20
10
0
0
10
20
30
m 1.00532 c 334.956



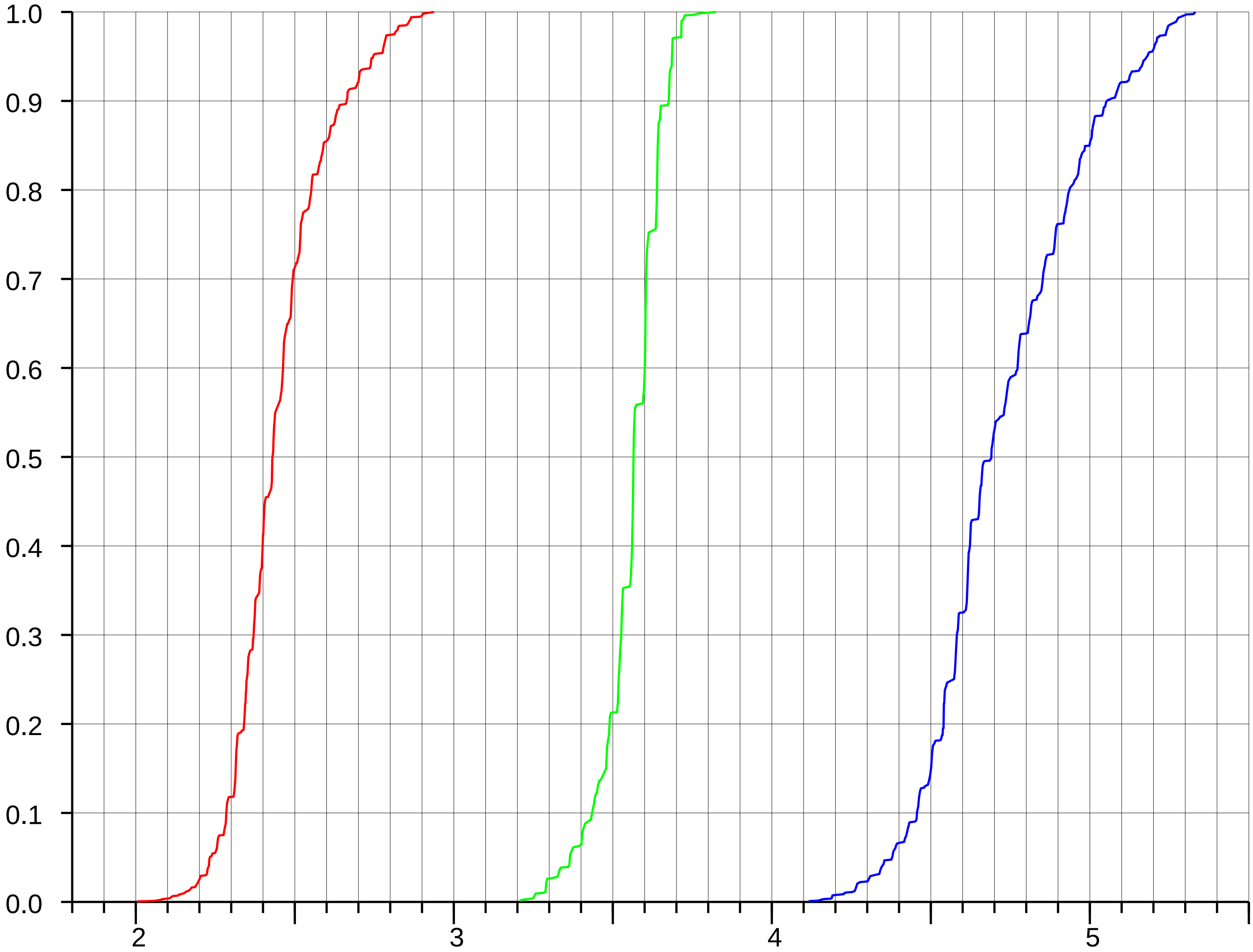
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
3.5
3.0
2.5
2.0
1.5
1.0
0.5



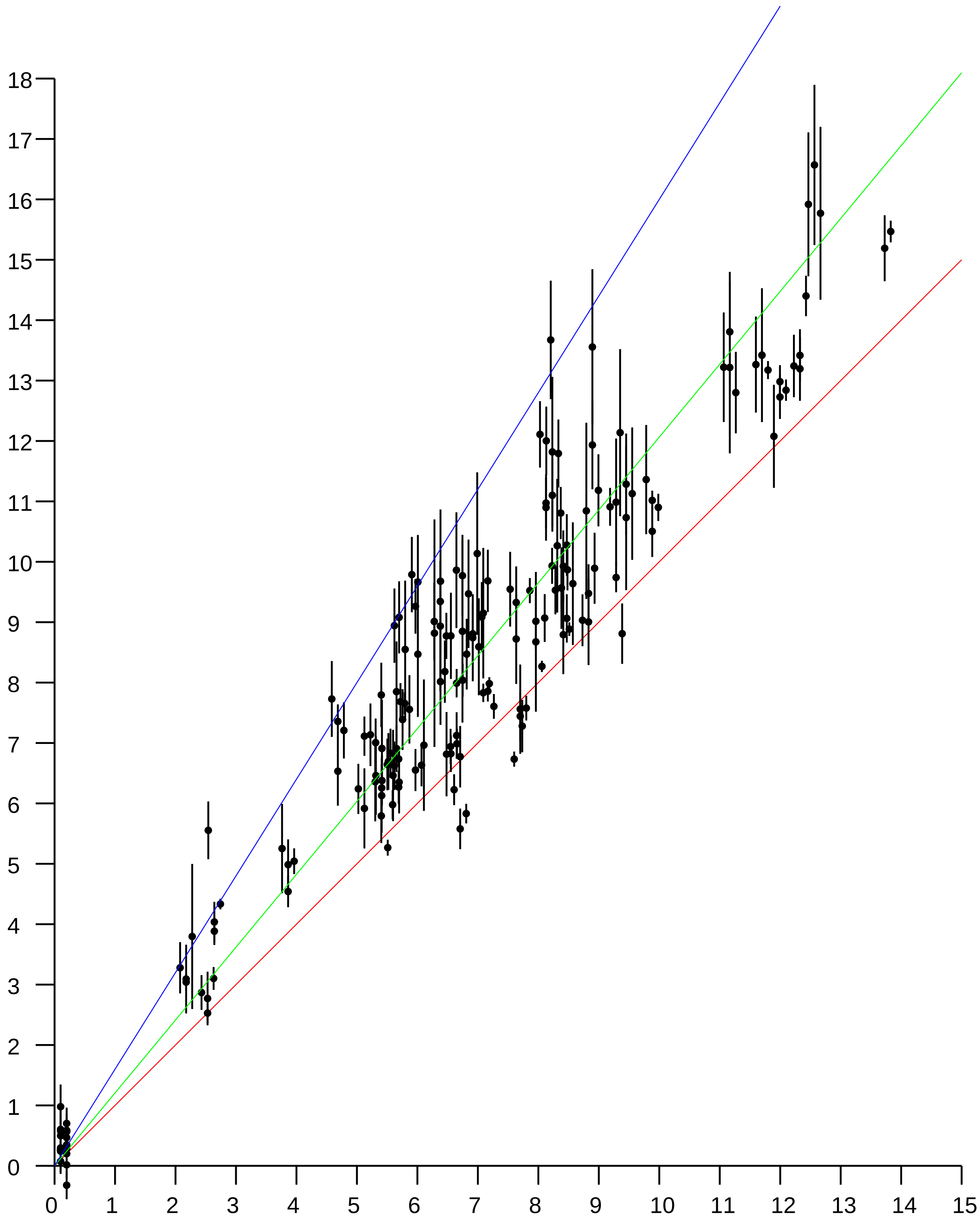
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
10
20
30
3.5
3.0
2.5
2.0
1.5
0.5
1.0



4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3.5
3.0
2.5
2.0
1.5
0.5
1.0
0
10
20
30
40
50
60



Google Wifi 5 GHz band, 80 MHz BW, distances 1, 2, and 3 meters



Horizontal: actual distance (meter)

Vertical: measured distance (meter)

red line: slope 1

green line: slope 1.2 (best fit)

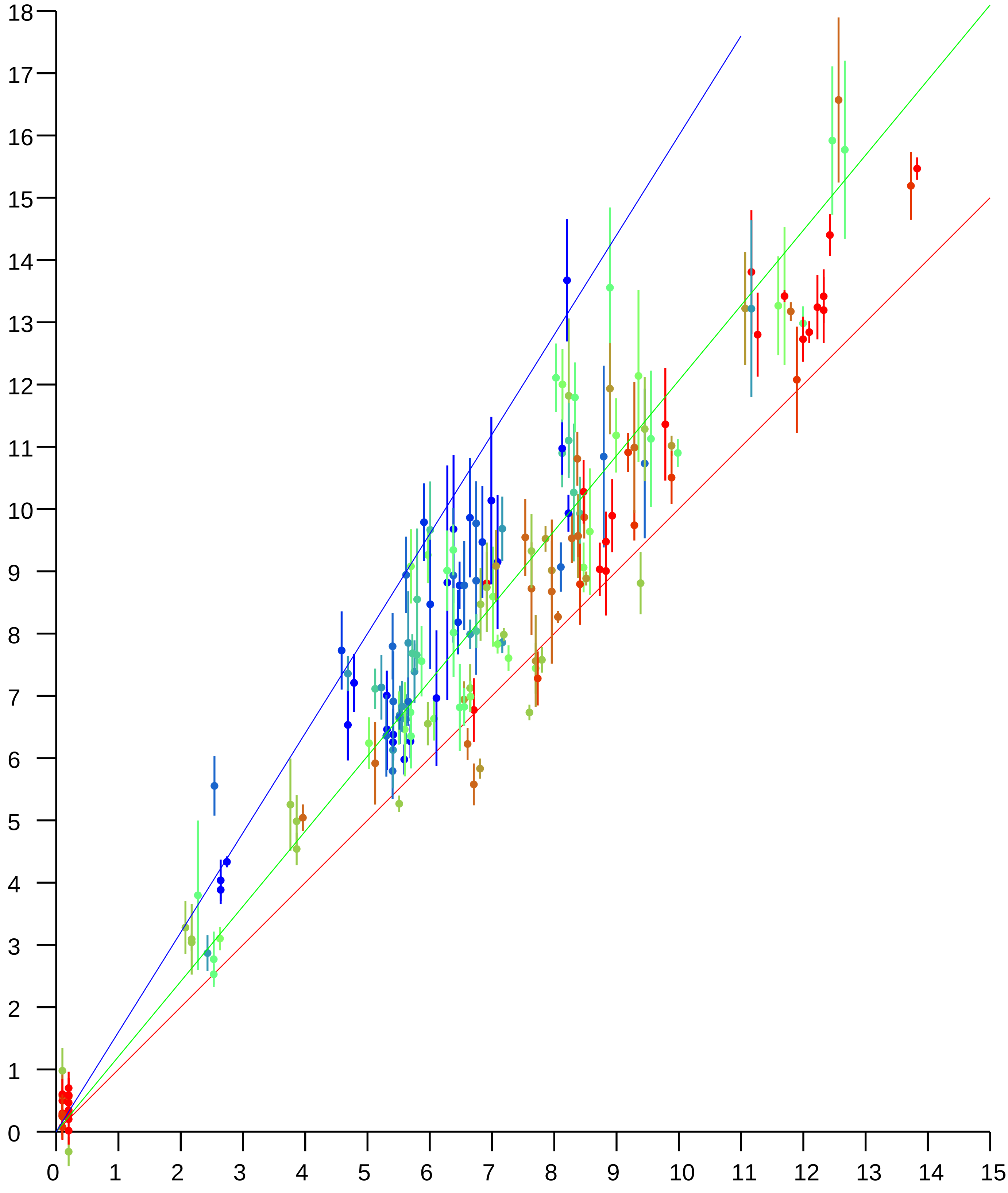
blue line: slope 1.6

Relative Permittivity of Building Materials

Plasterboard	2.02
Gypsum	2.41 – 2.60
Plywood	3.67 – 3.81
Brick	3.88 – 4.62
Wood	3.92 – 5.89
Glass	6.06
Concrete	7.63 – 9.54
Tissue	28 – 50

(*) “Permittivity and Conductivity Measurements of Building Materials at 5.8 GHz and 41.5 GHz,” Iñigo Cuiñas and Manuel García Sánchez, *Wireless Personal Communications* **20:** 93–100, 2002.

(*) “Time-Domain Free-Field Measurements of the Relative Permittivity of Building Materials,” C.A. Grosvenor, *et al*, *IEEE Transactions On Instrumentation And Measurement*, **58:** 2275, 2009



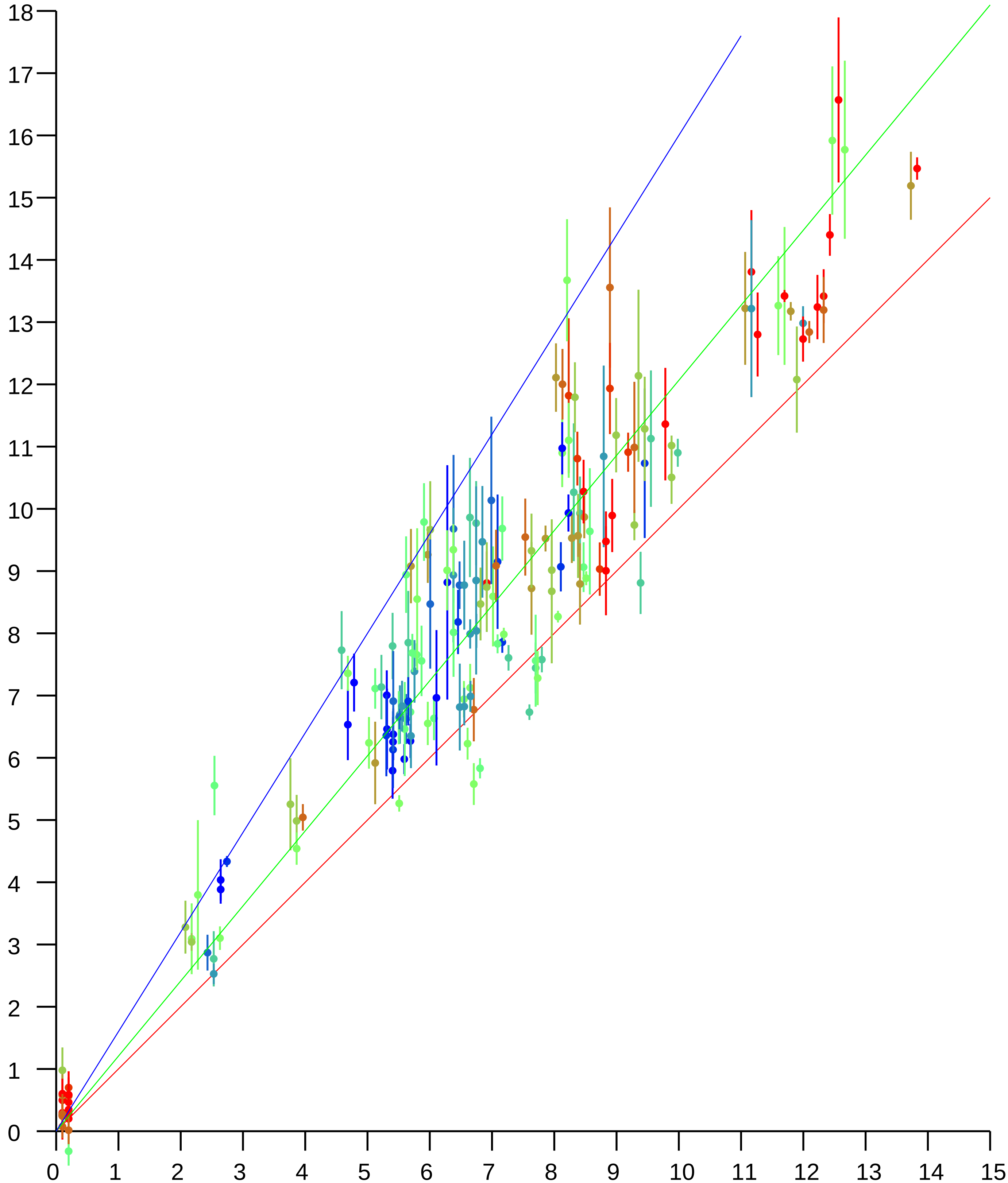
Horizontal: actual distance (meter). Vertical: measured distance (meter)

Red line: slope 1, Green line: slope 1.2 (best fit), Blue line: slope 1.6

Dot color code based on actual RSSI minus predicted RSSI

blue = -10dB, green = 0 dB, red = +10 dB

Where RSSI prediction is based on actual distance



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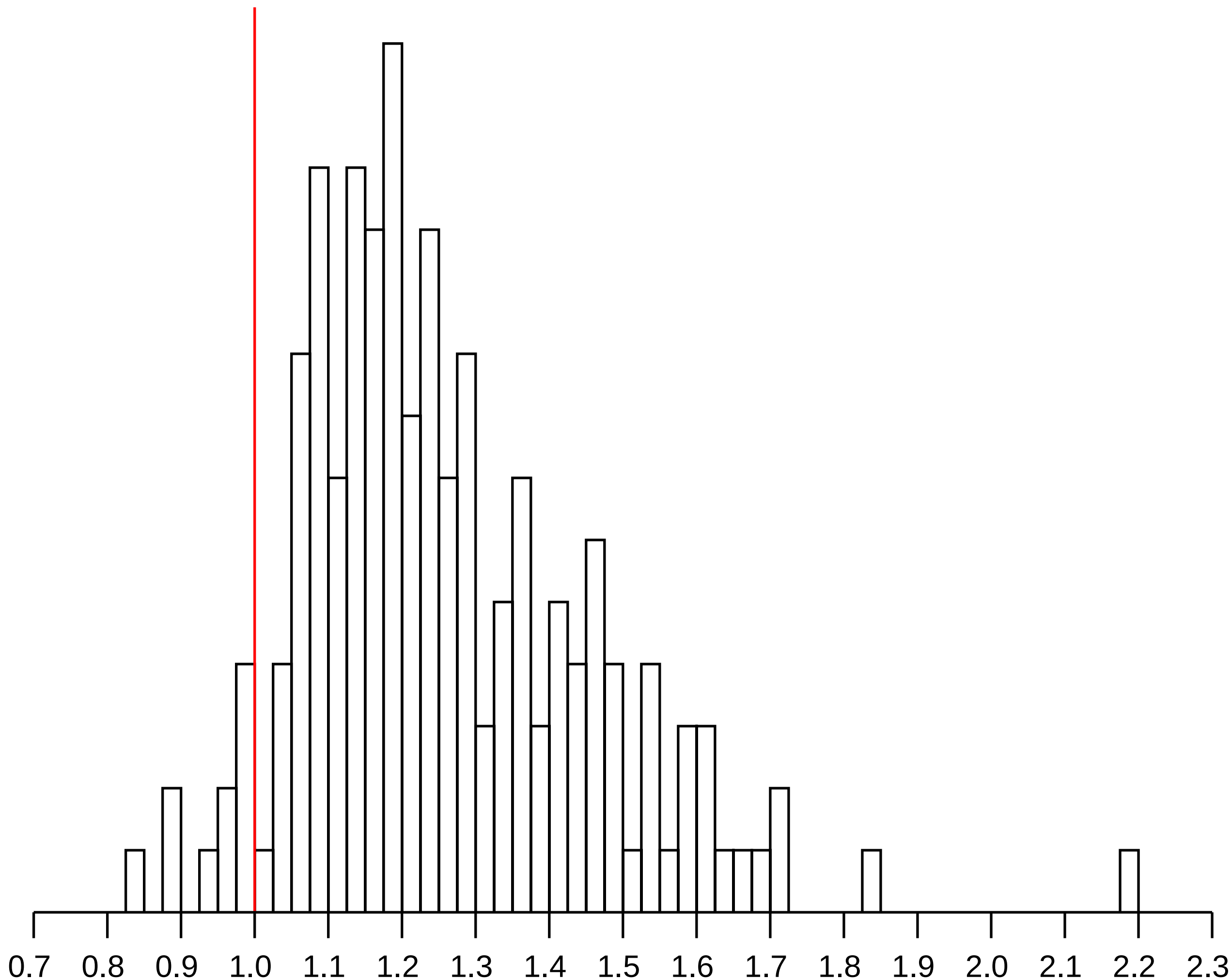
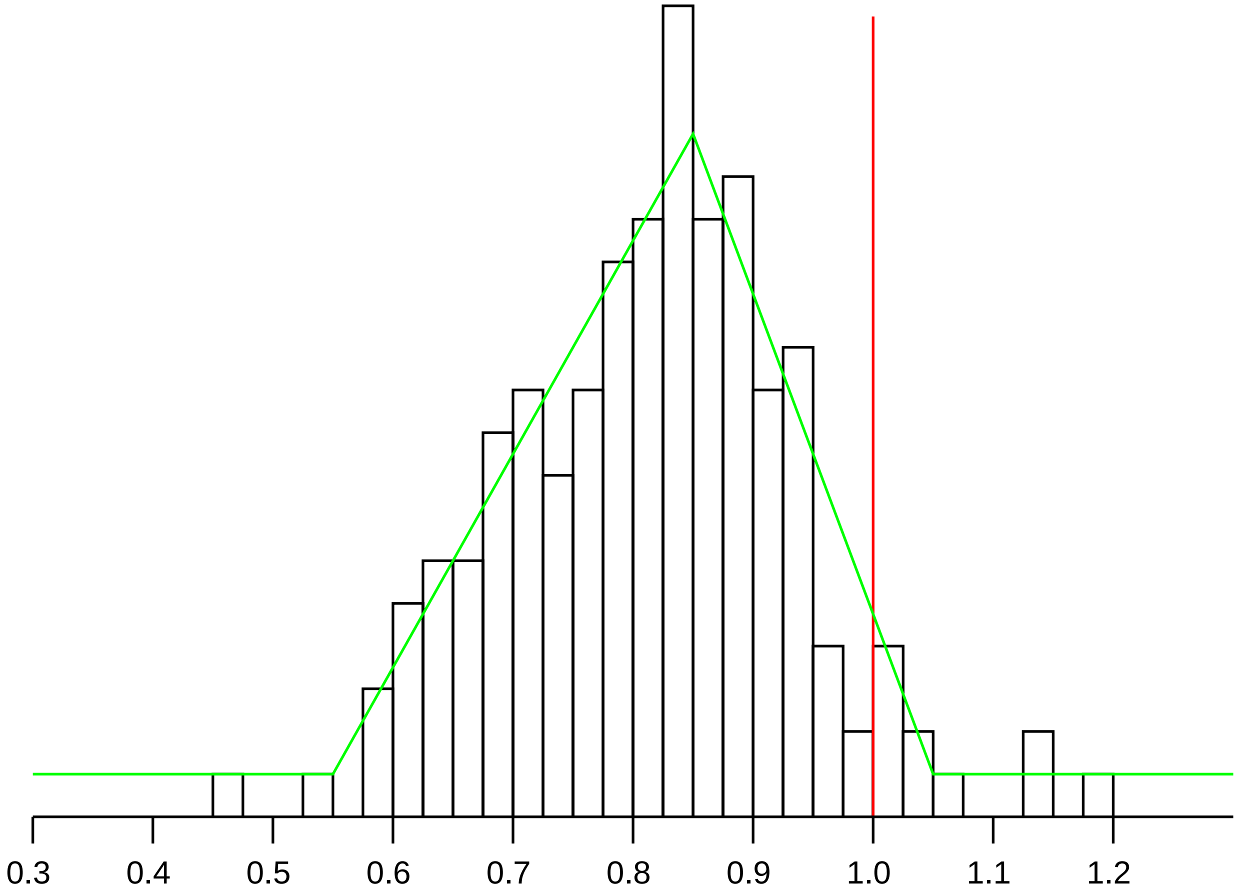


Horizontal axis: ratio of measured to true distance



Horizontal axis: ratio of true distance to measured distance

Green triangle: observation model for Bayesian update


09:32
21°
85%
FTMRTT
d 9.616 m
s 0.419 m
p -90 dBm
d 0.614 m
s 0.259 m
p -61 dBm
d 7.254 m
s 0.204 m
p -85 dBm

15:49 28° 92%

FTMRTT

Bayesian Grid Update

At each time step, measure distances and:

- Apply transition model (random walk), and
- Apply observation model (use Baye's rule)

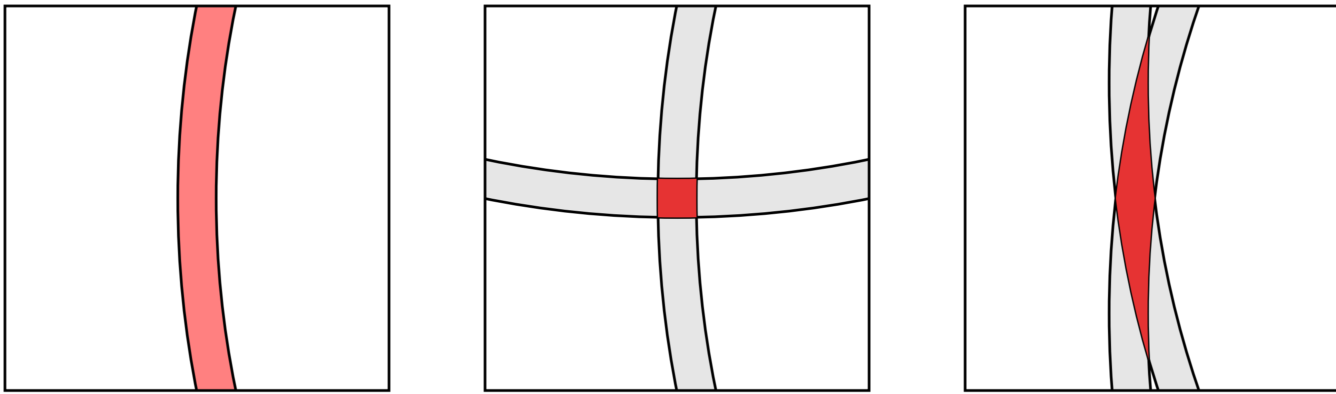
Bayesian Grid Update

At each time step, measure distances and:

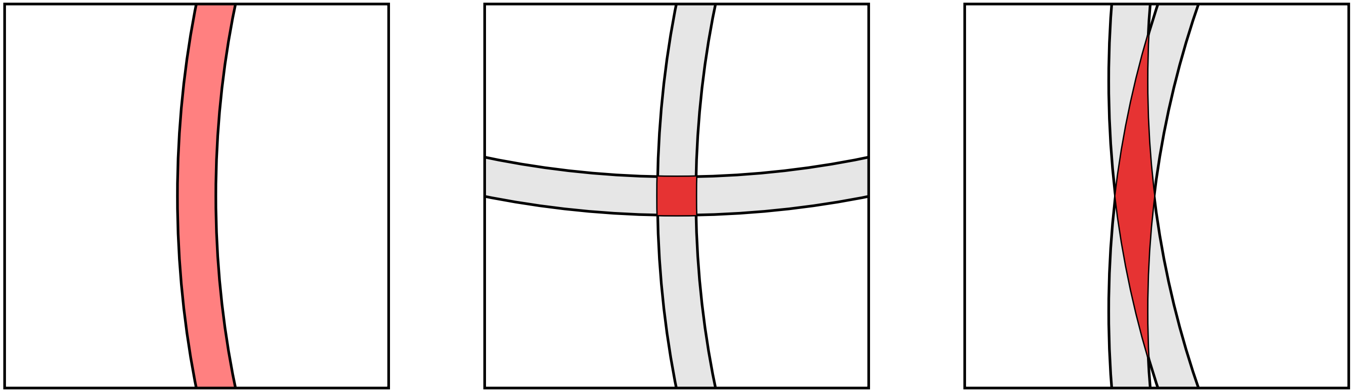
- Apply transition model (random walk), and
- Apply observation model (use Baye's rule)

For single position output, compute:

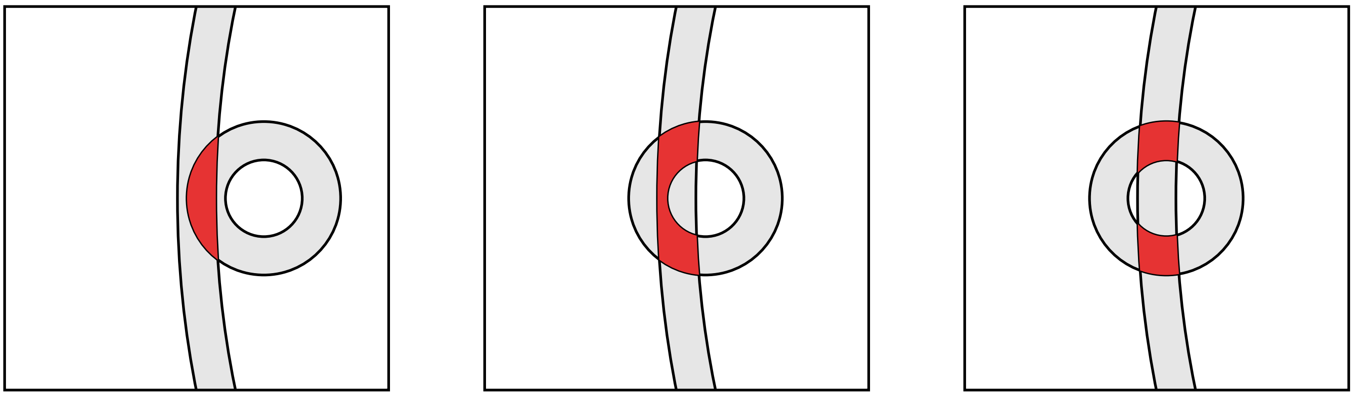
- Maximum likelihood (peak), or
- Expected value (centroid)



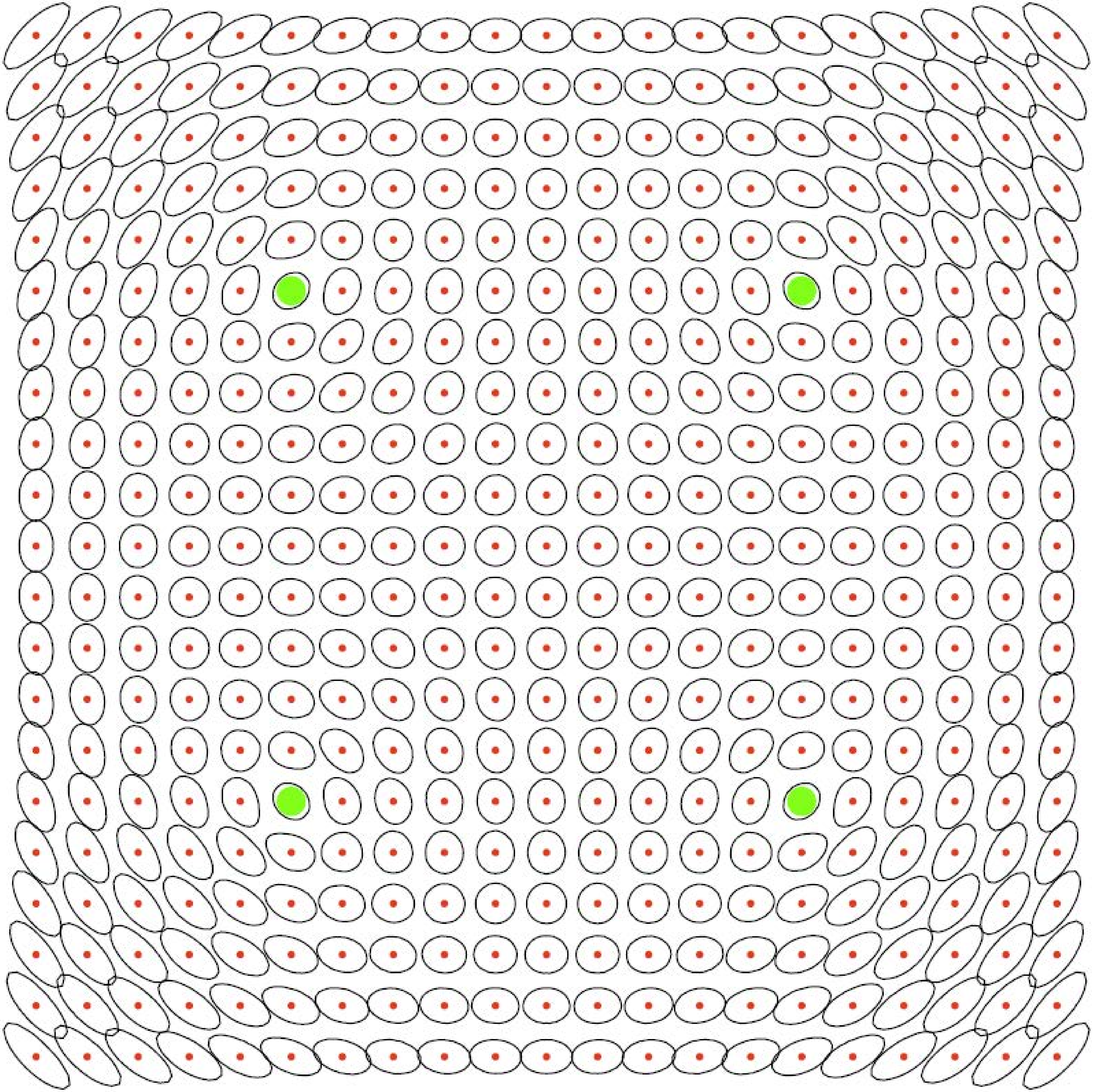
Dilution of Precision (noise gain): 1/sin(θ)

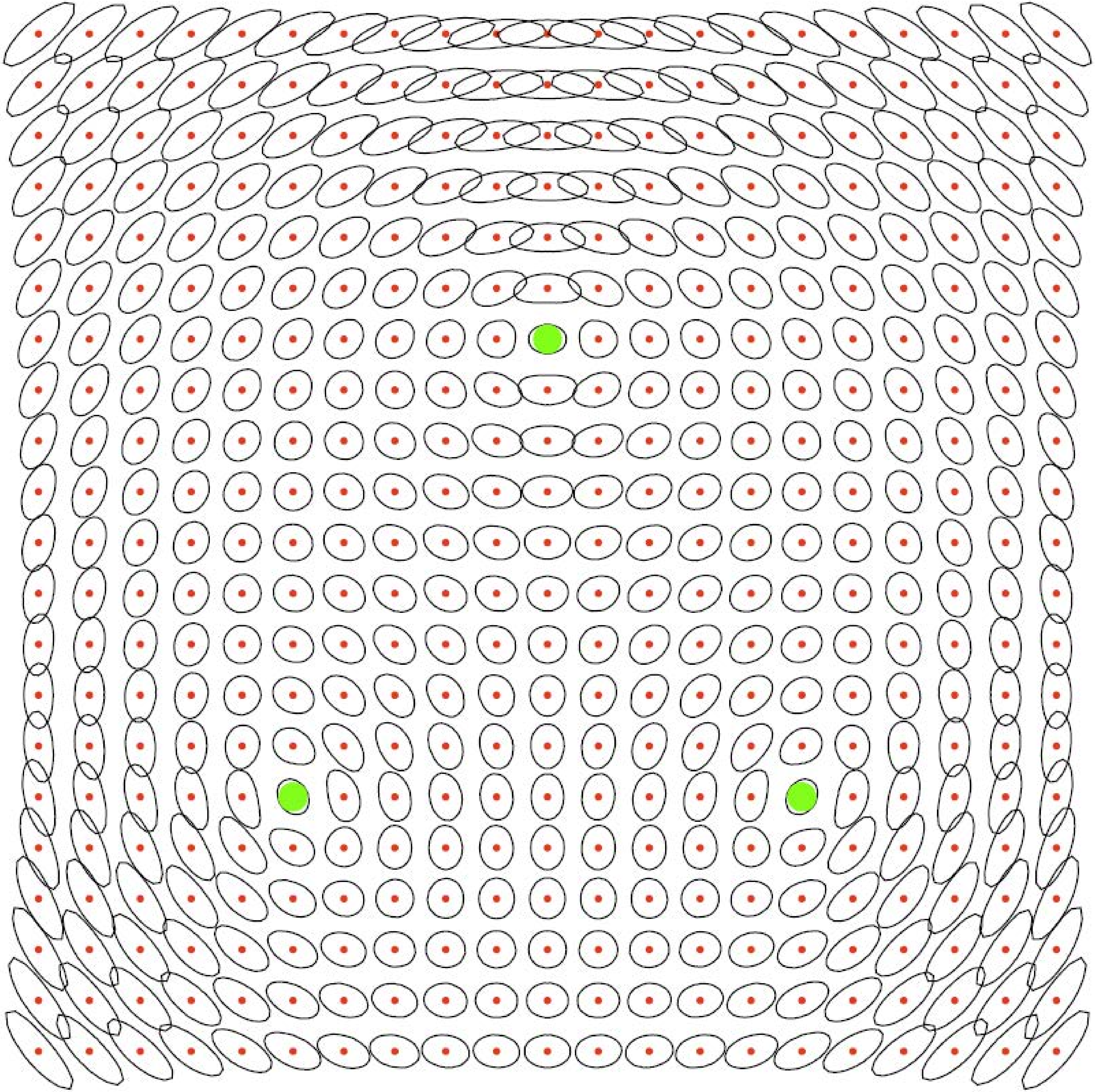


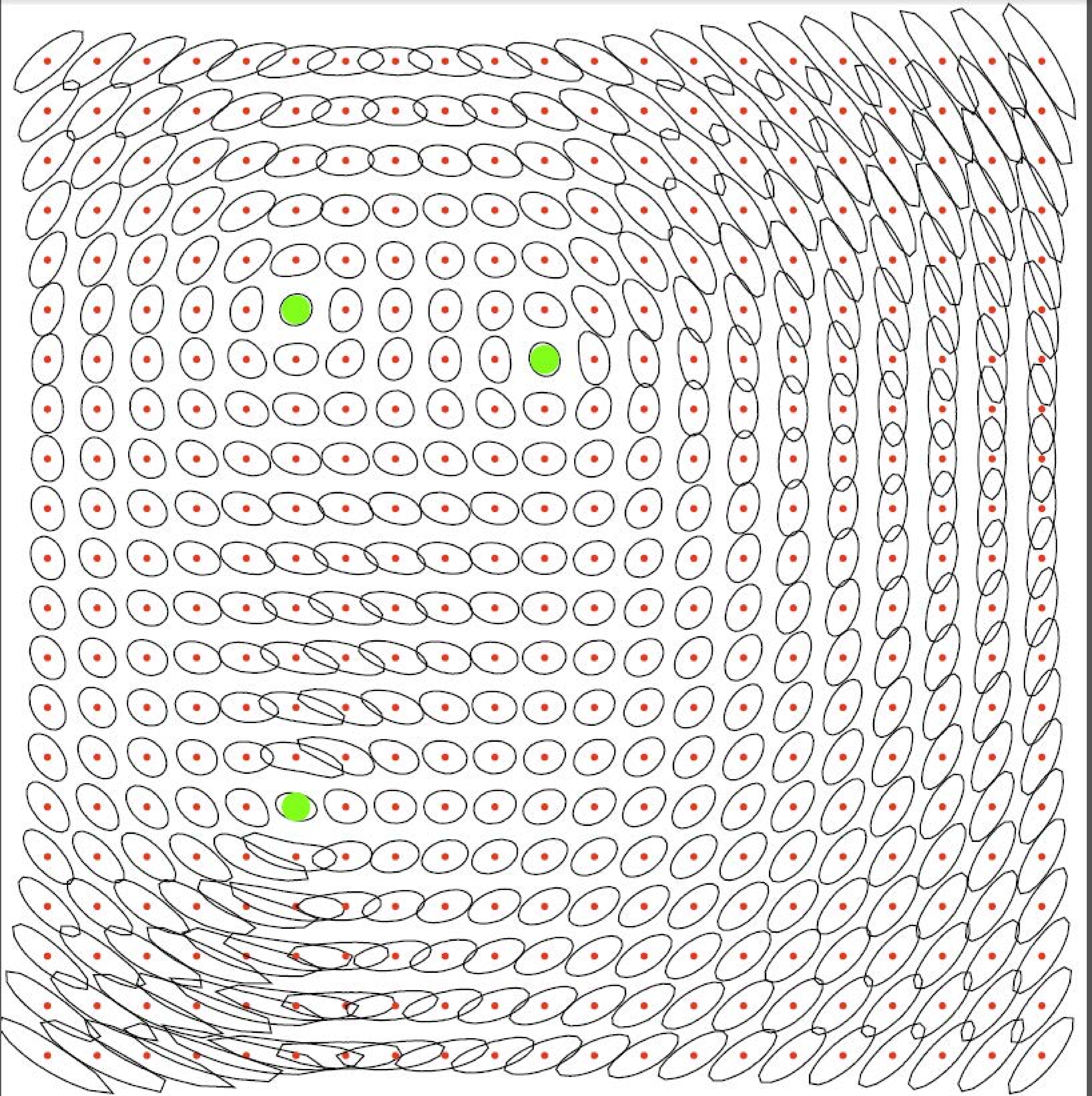
Dilution of Precision (noise gain): $1/\sin(\theta)$

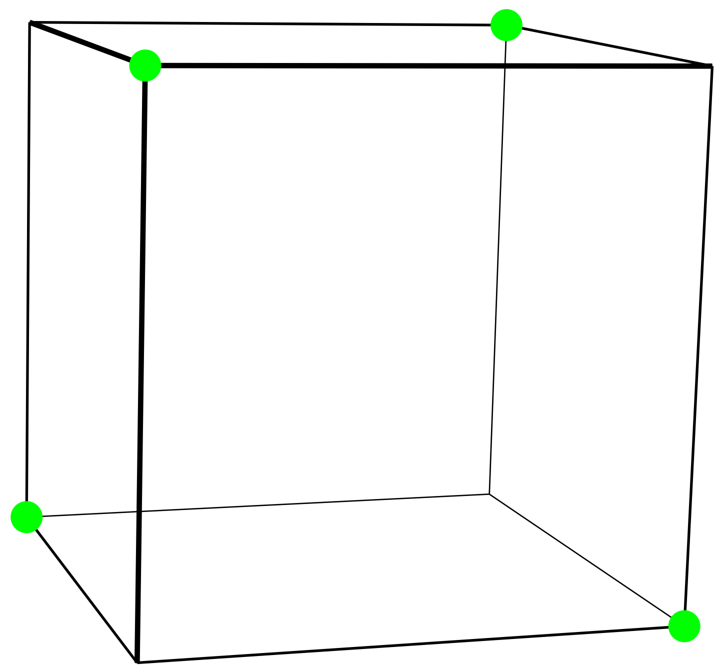


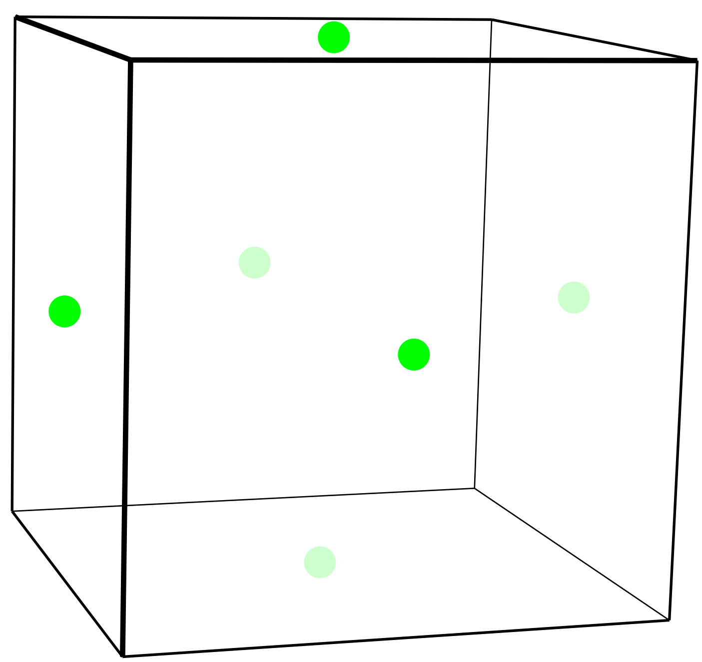
Close up (non linear) case





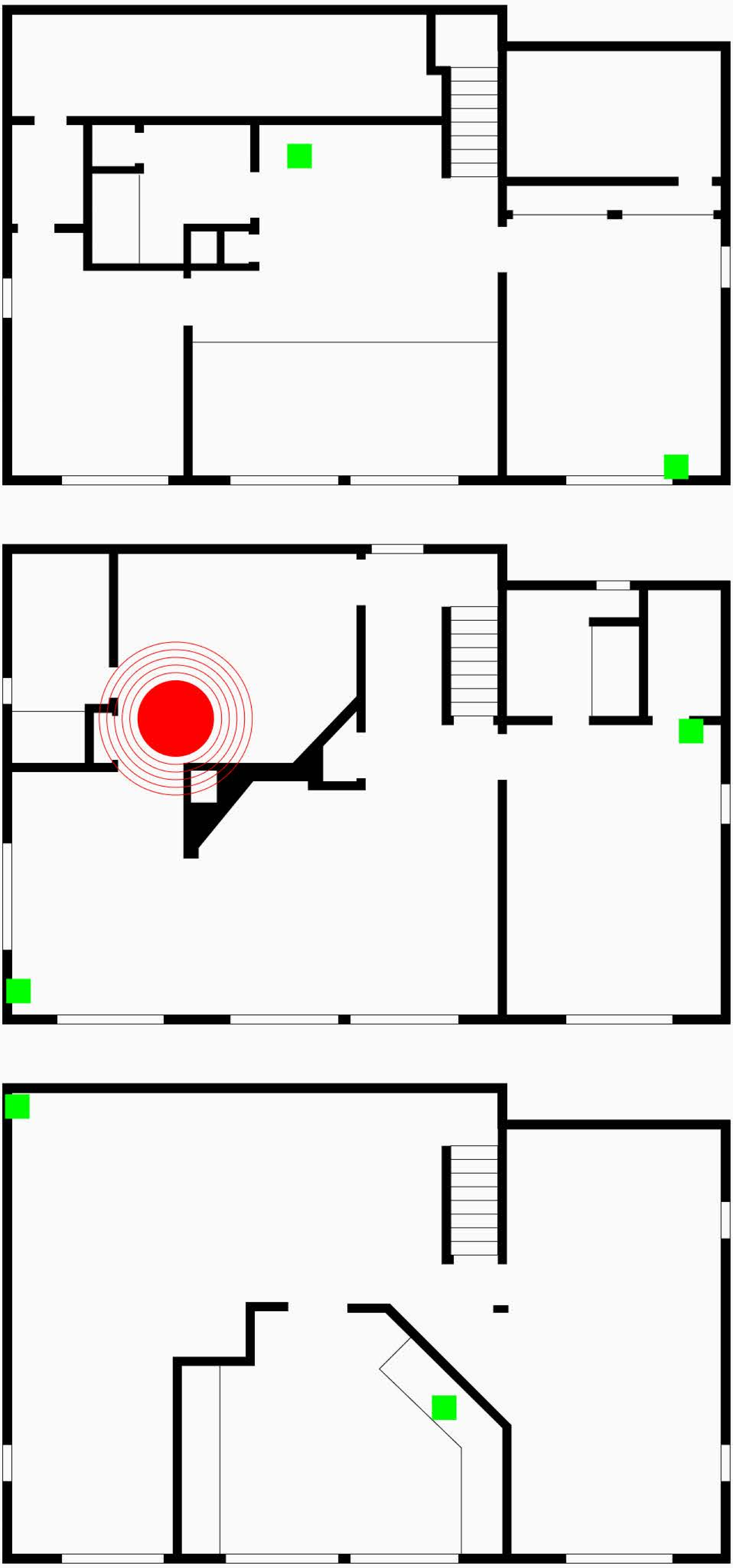






2:10 65%

FTMRTT



Is the location accuracy high enough?

- 10 m – 20 m ✗
- 1 m – 2 m ?
- 0.1 m – 0.2 m √

Will it “scale”?

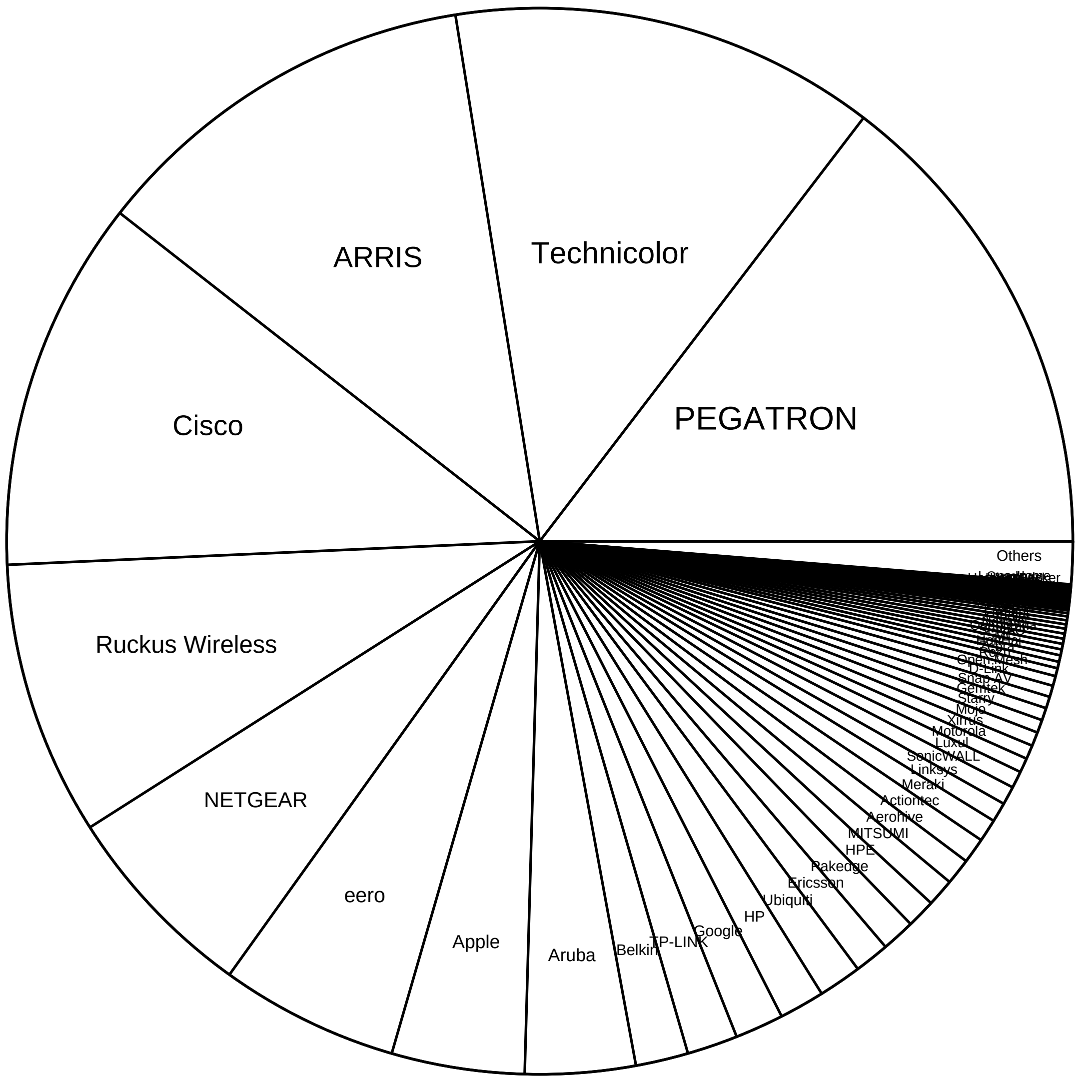
- Hundreds at Honolulu Symphony trying to find their seat
- Knock out Google Wifi mesh with FTM RTT “DOS attack”
- Need “passive” “GPS-like” system
- Can be done if APs communicate and broadcast results.
- Unclear if clock synchronization can be accurate enough.

Privacy

- User needs to give app permission
- User needs to enable location services on device
- STA (phone) need not be connected to AP (WiFi)
- AP need not be connected to WLAN (internet)
- MAC address is randomized
- AP cannot determine RTT
- FTM RTT disabled when app is in background
- But: Neighbour Awareness Networking (NAN)?

What is the competition?

- BLE beacons + phased array direction measurement.
- Low cost, low power, small size.
- Not tied into Wifi AP infrastructure
- Will it work?
- Will it work accurately enough?



18,008 WiFi APs (unique global MAC addresses) in Back Bay

SSID The Promised LAN
SSID WayFi
SSID NoWires
SSID Aloooooha 5g
SSID Issa not your wifi
SSID Stay-Off-Our-Network
SSID Mo money No wifi
SSID Don't even try!
SSID No Free Parking
SSID IWillHackYouAsWell
SSID BuzzOff
SSID Looking for networks...
SSID Loading, Please Wait
SSID Access_Denied
SSID OutOfService
SSID Biohazard
SSID trojan.exe
SSID It hurts when IP
SSID Mahalo
SSID Unconfigured SSID 4
SSID Abandwidthwaitingfor2
SSID Make Wifi Great Again
SSID Pretty Fly for a Wi-Fi
SSID FBI Surveillance Team Bravo
SSID NSA_Guest
SSID Abraham Linksys
SSID The password is password
SSID ClickHereForWifi
SSID ClickHereForAGoodTime
SSID FlywireGuest
SSID 5GSpot
SSID HIDE YOUR KIDS HIDE YOUR WIFI
SSID OfCourseIBelieveThat
SSID Lobstah
SSID Paak the Caa
SSID Bizarro_iFiW
SSID We Can Hear You Having Sex!
SSID WittyWifiName
SSID Les amis des tutus
SSID “Yeah, baby”
SSID Engineering, Biotech, and Beer
SSID DropitLikeaHotspot
SSID DissentIsPatriotic
SSID husbandishome306
SSID AgNO3
SSID "来啊"
SSID "за гости"
SSID "🐼"

FTMRTT

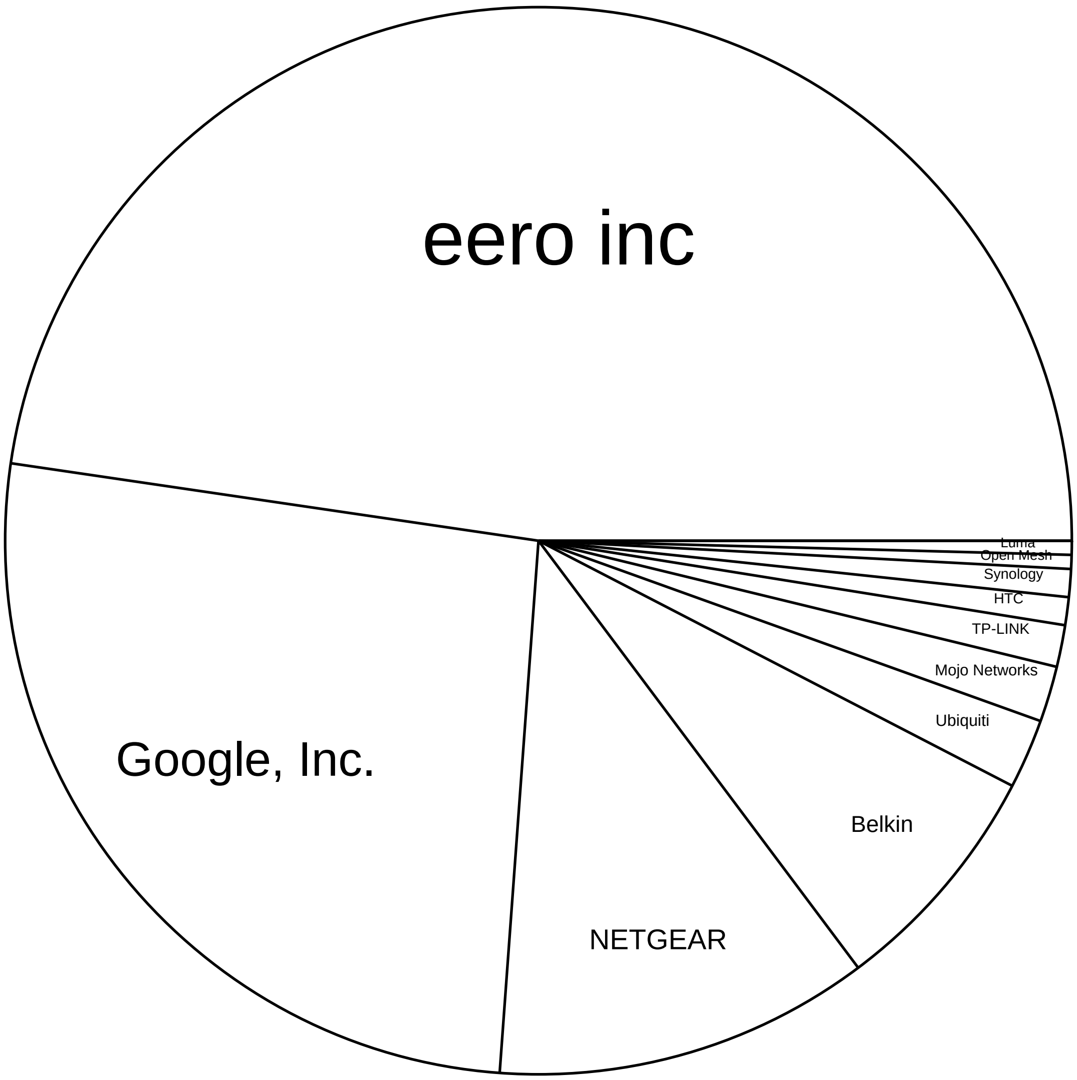
No RTT responses from 99 APs

```
 0 94:91:7f:48:3c:b2  -60 2432 40 MySpectrumWiFib4-2G
 1 82:14:29:ed:96:e0  -60 2412 20 Douglas Farrell's Gu…
 2 50:09:59:73:f6:28  -61 2462 20 Pretty Fly
 3 80:29:94:53:e7:0e  -62 2462 20 TC8717T08
 4 08:95:2a:15:f5:24  -64 2412 20 UNSULLIED WIFI
 5 b0:39:56:b3:6b:39  -64 2447 20 ks wifi pool_22
 6 a8:9a:93:9b:ca:b6  -65 2412 20 MySpectrumWiFib0-2G
 7 60:d0:2c:22:f5:a9  -65 2437 20 RitzCarlton_RESIDENC…
 8 20:e5:2a:06:37:43  -66 2457 20 NETGEAR33
 9 50:09:59:c2:1a:23  -66 2412 20 black
10 d8:a7:56:67:f8:be  -67 2412 20 MySpectrumWiFib8-2G
11 60:d0:2c:23:57:69  -68 2437 20 RitzCarlton_RESIDENC…
12 a0:39:ee:60:18:36  -68 2437 20 MySpectrumWiFi30-2G
13 10:0d:7f:e4:e1:ab  -68 2462 20 01110111 01101001 01…
14 20:4e:7f:56:85:14  -69 2417 20 Keei
15 34:6b:46:4e:4c:1a  -69 2437 20 MySpectrumWiFi14-2G
16 6c:b0:ce:ee:44:31  -70 2452 20 NETGEAR02
17 00:19:be:29:07:ff  -71 5745 20 BGS
18 60:d0:2c:63:57:68  -71 2437 20
19 4c:60:de:2d:82:3e  -72 2442 20 Kaiolu 403
20 20:e5:2a:17:75:42  -73 2442 20 NETGEAR30
21 12:19:be:29:07:ff  -74 5745 20 Waikiki.com
22 94:91:7f:48:3c:b3  -75 5200 80 MySpectrumWiFib4-5G
23 60:d0:2c:a3:57:6c  -75 5825 20
24 ec:58:ea:54:bd:ec  -76 5825 20
25 ec:58:ea:94:bd:ec  -76 5825 20
26 ec:58:ea:d4:bd:ec  -76 5825 20
27 ec:58:ea:14:bd:ed  -76 5825 20 RitzCarlton_RESIDENC…
28 60:d0:2c:63:57:6c  -76 5825 20
29 60:d0:2c:23:57:6d  -76 5825 20 RitzCarlton_RESIDENC…
30 00:19:be:29:08:07  -76 5745 20 BGS
31 60:d0:2c:e3:57:6c  -76 5825 20
32 60:fe:20:dc:91:32  -76 2427 20 HT066
33 12:19:be:29:08:07  -77 5745 20 Waikiki.com
34 20:e5:2a:06:37:42  -77 5765 40 NETGEAR33-5G
GPS 21.282213 -157.828692  alt 33 acc 6
```

No RTT responses from 99 APs

SSID 01110111 01101001 01100110 01101
SSID OooSzechuanSauce
SSID 5Ghz Imperial Defence Network
SSID 56k_fax_modem
SSID =^..^=
SSID AdventurousShark
SSID aloha.aloha.aloha
SSID Audi_MMI_4040
SSID catfood 5GHz
SSID Central Perk-5G
SSID Da Hi Life-5G
SSID Dakine Wifi
SSID Drama Queen Guest
SSID Drybar Guests
SSID Edo
SSID EMPTEE
SSID Exhale Hawaii
SSID FBI Surveillance Van
SSID Fish Head Jar
SSID Found Residences Waikiki
SSID Free Wifi
SSID GallowsDancer
SSID GetYourOwn
SSID goHawaii Free WiFi
SSID Hang10
SSID Housekeeping
SSID Ice Monster Hawaii Guest
SSID ISeeYou!!!
SSID IU Sucks
SSID Jack's Wi-Fi Network
SSID Kapu
SSID Koi Pond
SSID Kokua
SSID Mohamed's Wi-Fi Network
SSID My WiFi
SSID NanaNene
SSID RedDirt
SSID Roosterhome
SSID Sandworms Lair
SSID Seaweed
SSID Standard Parking
SSID Tesla Guest
SSID Trina Turk IM
SSID Universal
SSID Waikiki
SSID WhiteDragonHorseInDaHouse
SSID 小倉理紗のiPhone
SSID 海賊王ですw_5GHz
SSID 경찰청 (Korean Police)
SSID whawaii.thai_net

- Broadcom 802.11ac Acculocate Access Point
- Intel® Dual Band Wireless-AC 8260
- Marvell AP-8964 802.11ac 4x4 Wave2 Concurrent Dual Band Access Point
- Mediatek MT663X 802.11abgn/ac Ref. STA
- Qualcomm IPQ4018 802.11ac 2-stream Dual-band, Dual-concurrent Router
- Qualcomm IPQ8065 802.11ac 4-stream Dual-band, Dual-concurrent Router
- Qualcomm Snapdragon™ 820 Development Kit
- Realtek RTL8812BU



236 FTM RTT (802.11mc) responders in Back Bay

WiFi Mesh Systems

- eero home WiFi system (Tri-band mesh WiFi)
- Google Wifi – AC1200
- Netgear Orbi – AC2200 (Tri-band mesh WiFi)
- TP-Link Deco M5 Whole Home Mesh WiFi System ?
- Linksys Velop – AC2200 (Tri-band Wifi Mesh System) ?
- Ubiquiti AmpliFi HD WiFi System ?
- Luma Whole Home Wifi (2 pack) ?
- ASUS Lyra Trio – AC1750 (Mesh WiFi System) ?
- HTC Managed Wi-Fi Service with Mesh Wifi ?
- . . .

No RTT responses from 55 APs

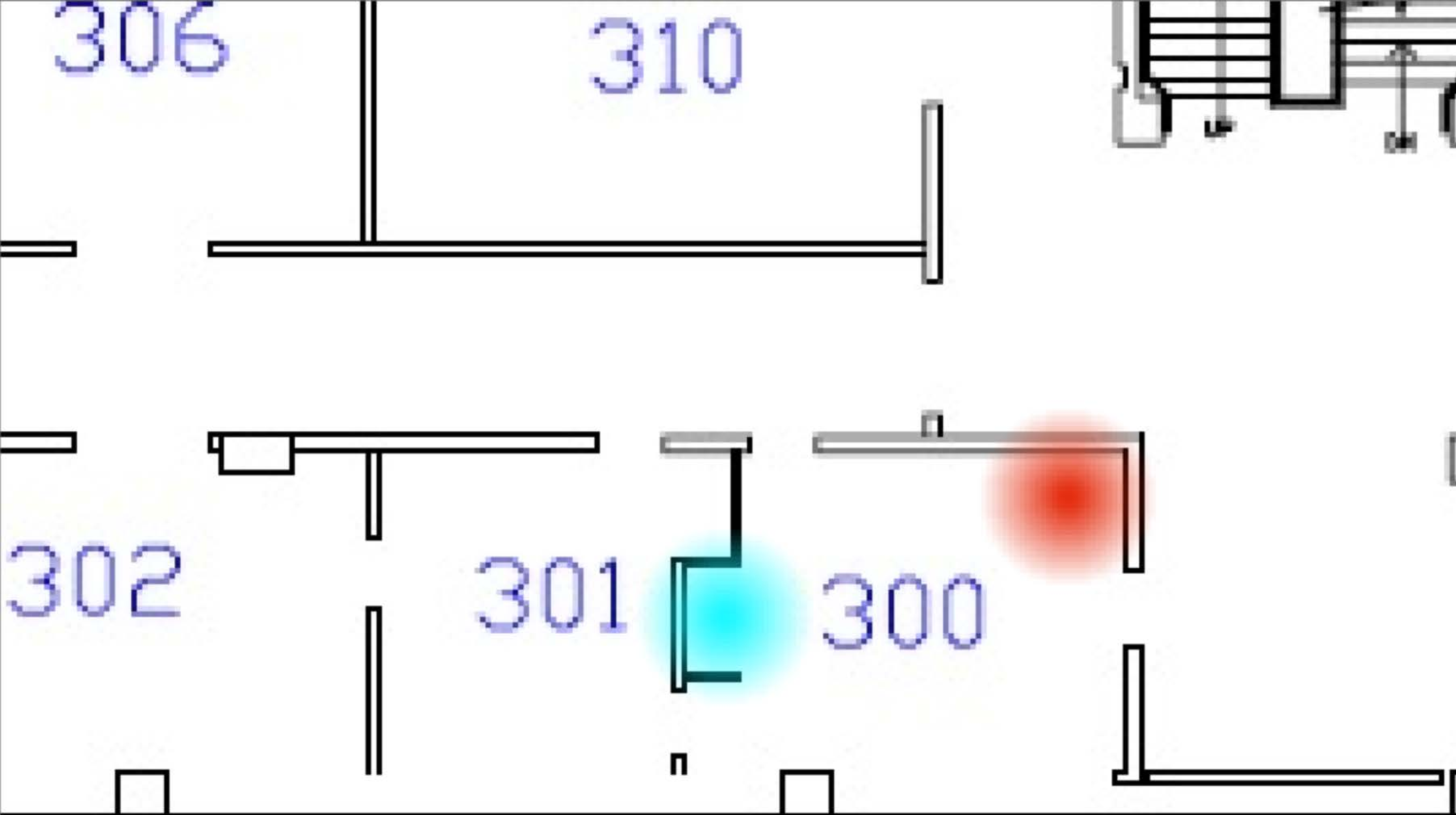
Use Wi-Fi

{34:fc:b9:74:59:e1=2462,-
66,4s}
{34:fc:b9:77:0e:
81=2437,-57,4s};(11)max=-65,
{34:fc:b9:73:d6:f1=5300,-
87,10s}
{40:e3:d6:19:e0:b1=5660,-
89,5s}
{34:fc:b9:77:0e:

UHM
[(3)
{34:fc:b9:73:d6:e0=2437,-
86,9s}
{34:fc:b9:74:59:e0=2462,-
66,4s}
{34:fc:b9:77:0e:
80=2437,-58,4s};(9)max=-68,
{40:e3:d6:19:e0:b0=5660,-
89,5s}
{34:fc:b9:76:aa:

DIRECT-CB-HP OfficeJet
Pro 8710
[(1)
{98:e7:f4:42:4c:cd=2412,-
75,5s};]

No RTT responses from 55 APs


306
310
302
301
300

suo sponte

suo motu

How far along are we?

- Boston Back Bay (July 2018) $236/18008 \approx 1.3\%$
- Waikiki (January 2019) $37/1275 \approx 2.9\%$
- Google WiFi (January 2019) turned on RTT bit in beacon frame

13:58 81°

Wifi points

Everything looks good and 3 Wifi points are online.

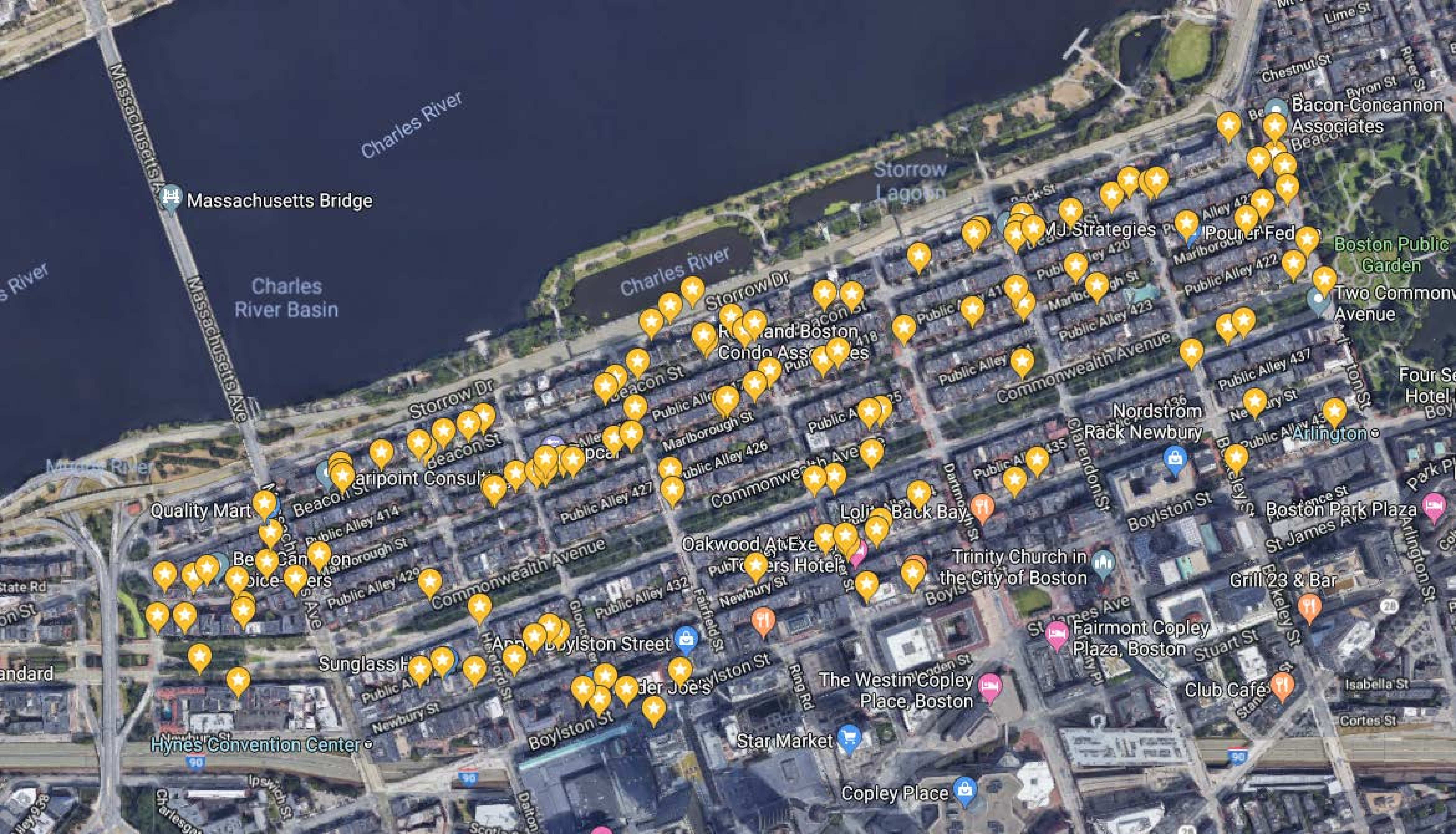
Info

Your Google Wifi just got better

Google Wifi installed an update at 1/14/2019, 1:12 PM HST. Here's what's new:
- IPv6: Support for devices on the guest network.
- IPv6 port opening.
- General stability & performance improvements.

DISMISS MORE DETAILS

Info



Charles River
Massachusetts Bridge
Massachusetts Ave
Charles River Basin
Charles River
Storrow Lagoon
Storrow Dr
Beacon St
Marlborough St
Commonwealth Avenue
Newbury St
Boylston St
Public Alley 414
Public Alley 429
Public Alley 427
Public Alley 426
Public Alley 432
Public Alley 420
Public Alley 422
Public Alley 423
Public Alley 437
Quality Mart
Hynes Convention Center
Nordstrom Rack Newbury
Trinity Church in the City of Boston
Grill 23 & Bar
Boston Park Plaza
Fairmont Copley Plaza, Boston
The Westin Copley Place, Boston
Star Market
Copley Place
Club Café
Bacon-Concannon Associates
MJ Strategies
Boston Public Garden
Arlington
Chestnut St
Byron St
Lime St
Clarendon St
Dartmouth St
Fairfield St
Hereford St
Berkeley St
St James Ave
Stuart St
Isabella St
Cortes St
Ring Rd
Ipswich St

Indoor navigation using WiFi round-trip time

Berthold K.P. Horn

- Fine Time Measurement (FTM) Round Trip Time (RTT)
- IEEE 802.11mc
- Background: Timing Advance (TA) in GSM and LTE
- Recovering initiator position from distances to responders
- Dilution of Precision (DOP)
- Non-Gaussian, non-stationary error
- Best spatial arrangement for responders
- Some issues, problems, and currrent limitations
- When will it happen?


15:51
28°
78%
FTMRTT
0 b8:08:cf:a0:8b
1 b8:08:cf:a0:88
2 b8:08:cf:a0:7a
3 b8:08:cf:a0:7a
4 b8:08:cf:a0:7a
5 b8:08:cf:a0:7a
6 0c:9d:92:b9:8f
7 38:8b:59:c4:f0
8 38:8b:59:c4:f3
9 38:8b:59:c4:f7
Continue WiFi Scanning
Range After Scan
Force Ranging
Write Log File
Get GPS Locations
Get Vendors from MAC
Run WiFi Scan Service
Use Fixed List of APs
Correct Range
Show Floor Plans
Keeep On Ranging
Signal Strength Tweak
Verbose Logging

Linear Equations for Four Transponders

With 4 responders we get 6 linear equations.

We can chose 3 that are linearly independent:

$$\begin{pmatrix} (\mathbf{r}_0 - \mathbf{r}_1)^T \\ (\mathbf{r}_1 - \mathbf{r}_2)^T \\ (\mathbf{r}_2 - \mathbf{r}_3)^T \end{pmatrix} \mathbf{s} = \mathbf{t}$$

where $\mathbf{t} = (t_{0,1}, t_{1,2}, t_{2,3})^T$ and $t_{i,j} = \big((d_j^2 - d_i^2) - (R_j^2 - R_i^2)\big)/2$.

Can solve 3 linear equations in 3 unknown components of $\mathbf{s}$

(provided $\mathbf{r}_0$, $\mathbf{r}_1$, $\mathbf{r}_2$, and $\mathbf{r}_3$ are not coplanar).

Linear Equations for Four Transponders

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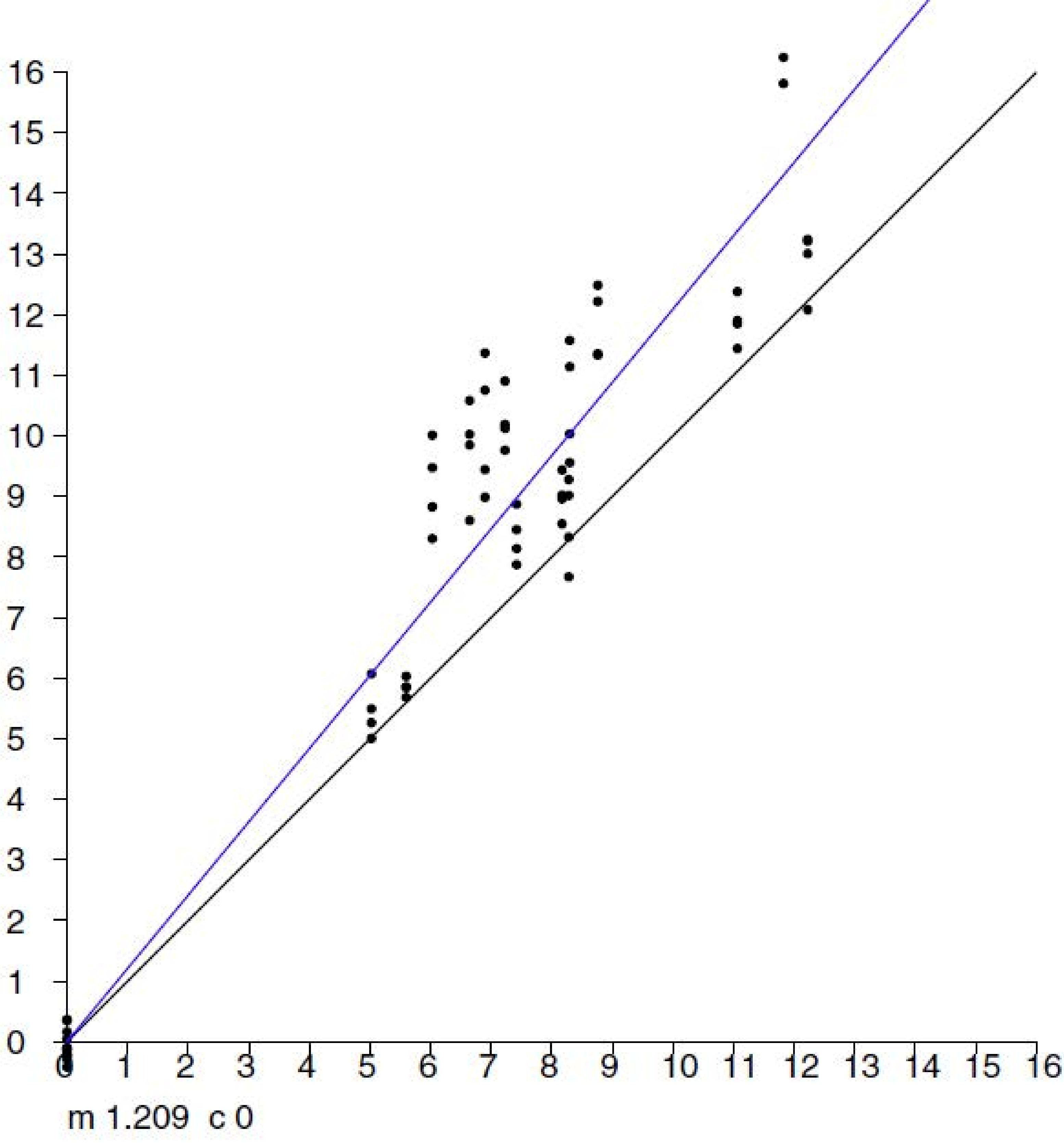
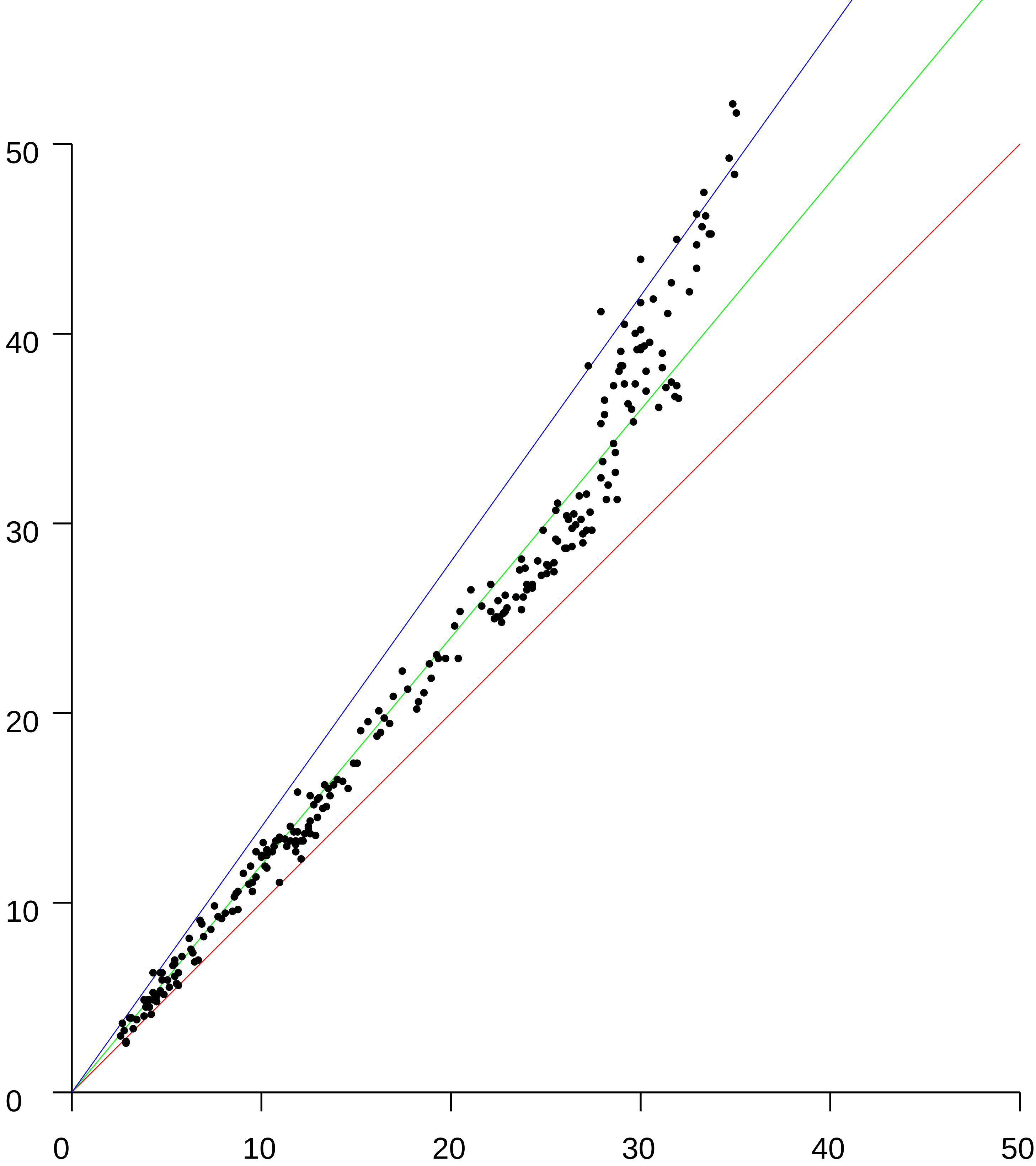
Can solve 3 linear equations in 3 unknown components of $\mathbf{s}$.

(provided $\mathbf{r}_0$, $\mathbf{r}_1$, $\mathbf{r}_2$, and $\mathbf{r}_3$ are not coplanar).

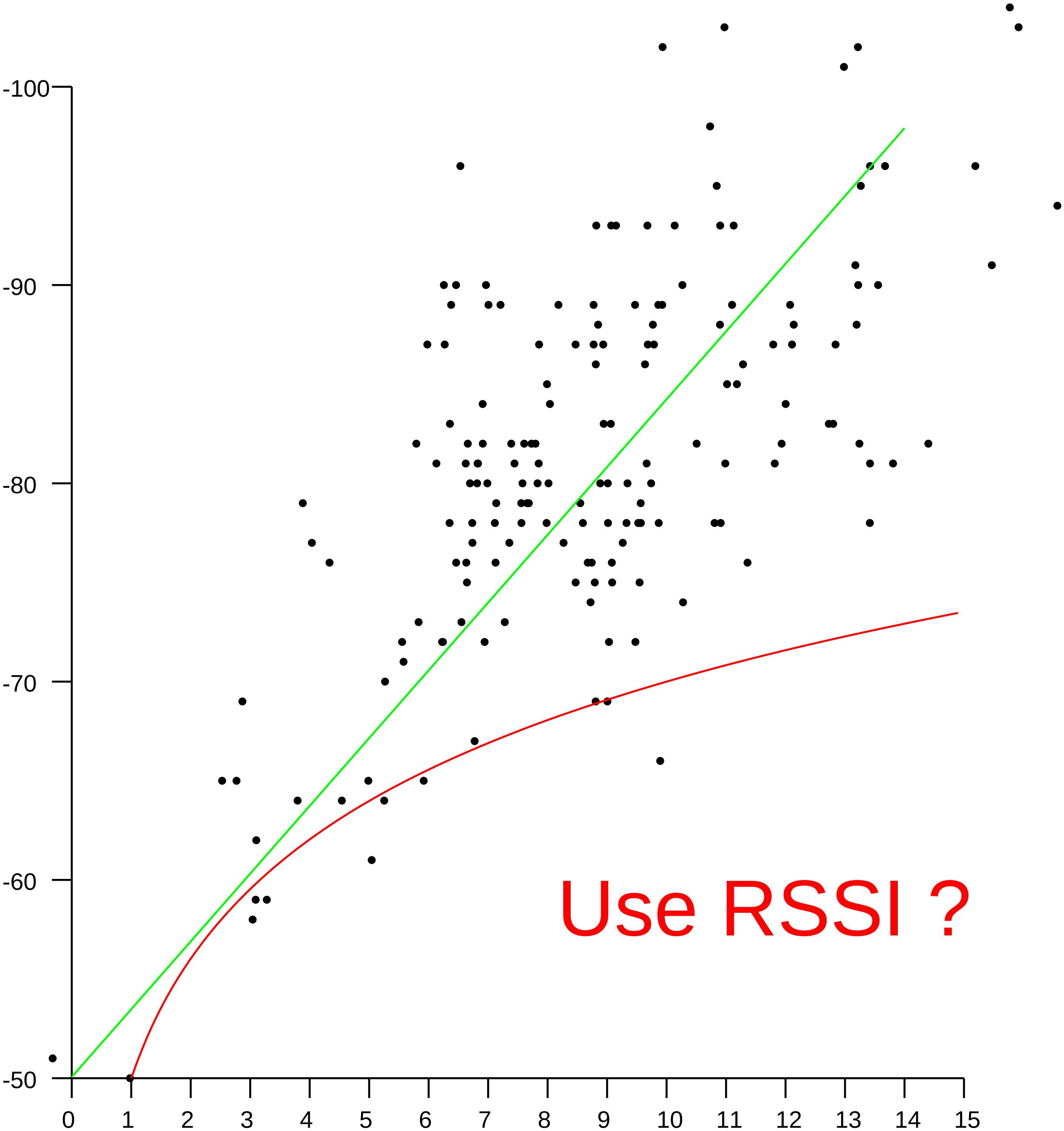
BUT: huge noise gain!



0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
m 1.209 c 0



Horizontal axis: actual distance (m)
Vertical axis: measured distance (m)
Open office setting - cubicles
Green line slope 1.2
Blue line slope 1.4

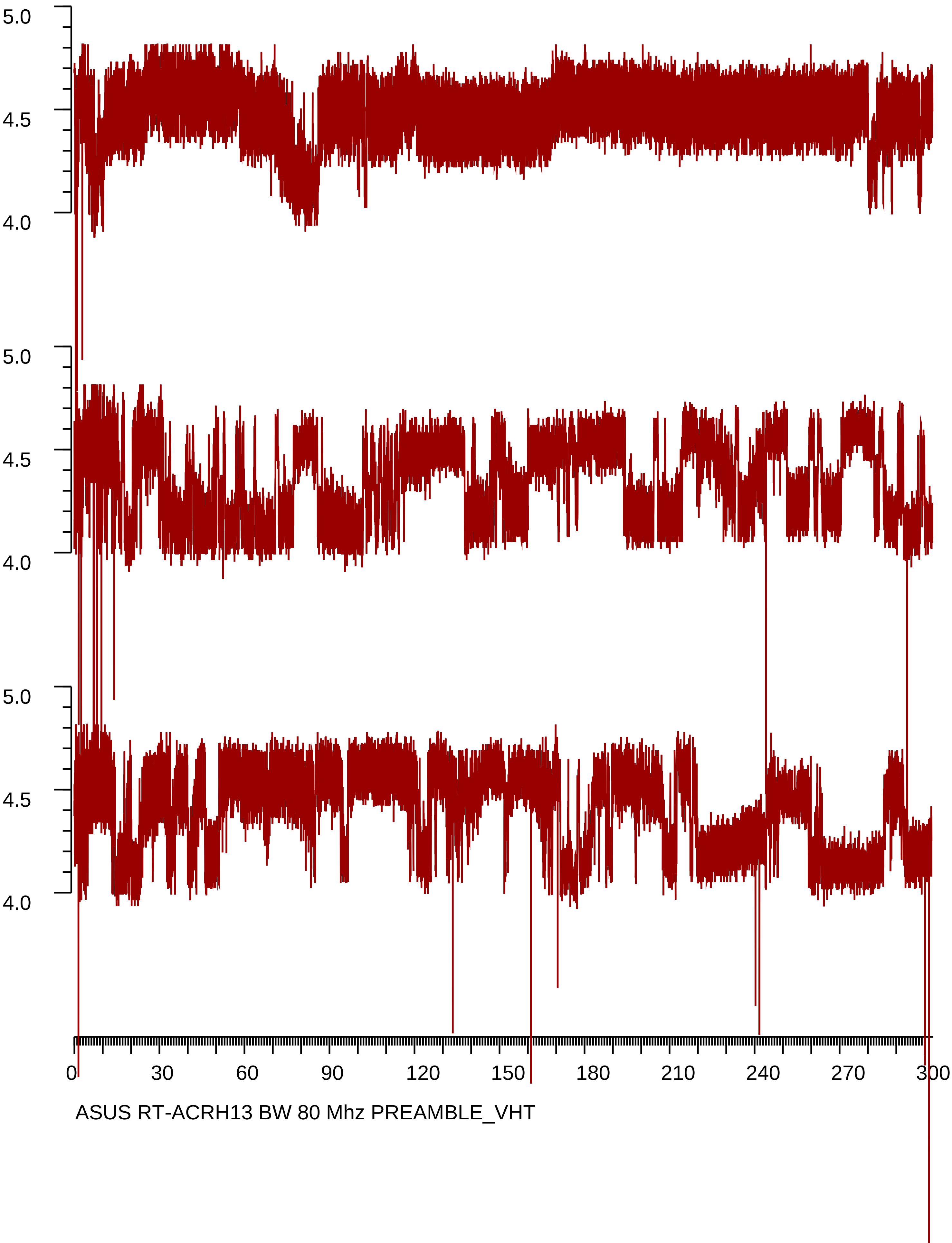


Horizontal axis: reported distance (meter)

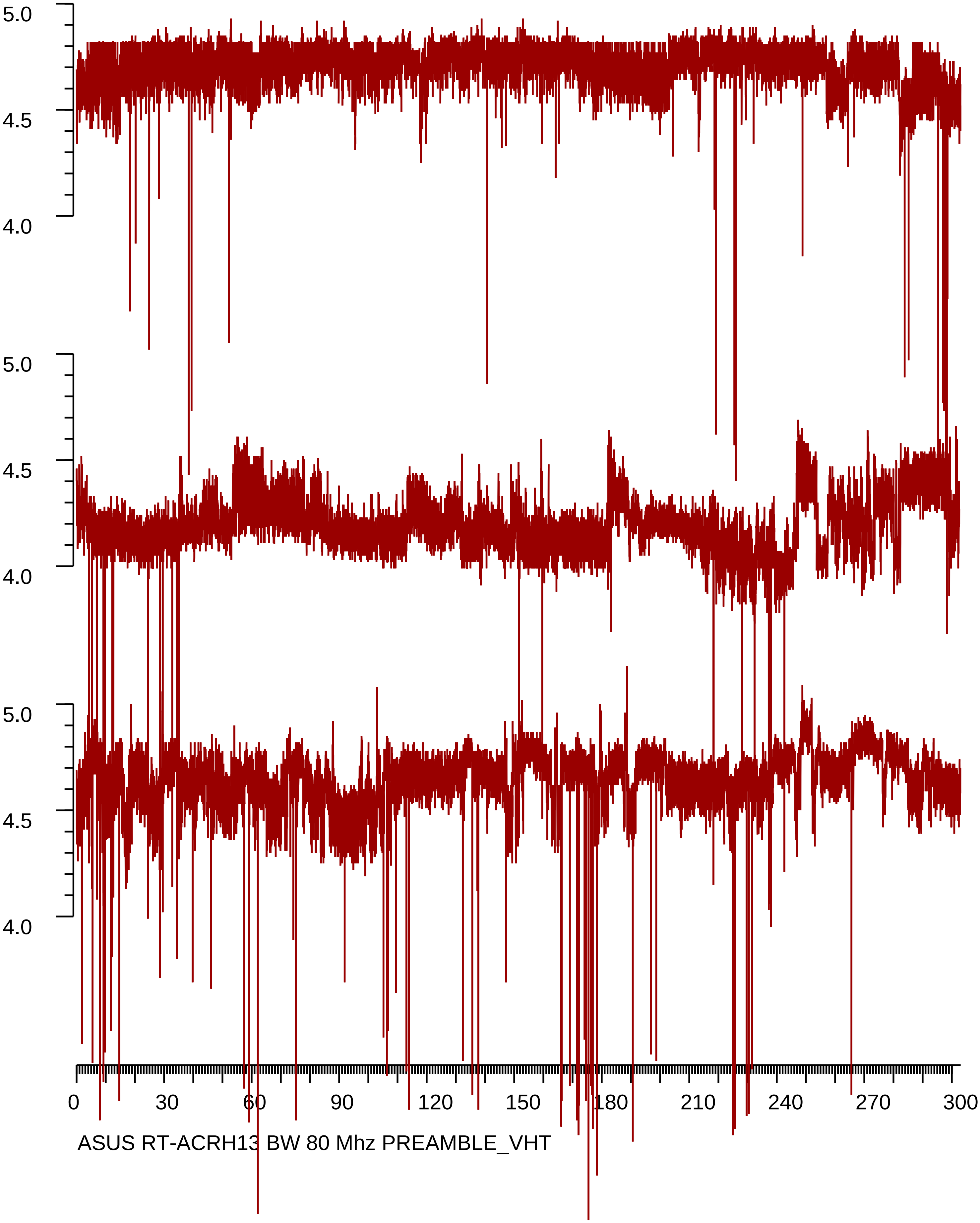
Vertical axis: signal strength (dBm)

Green line: linear fit -50 - 3.4 * R dBm

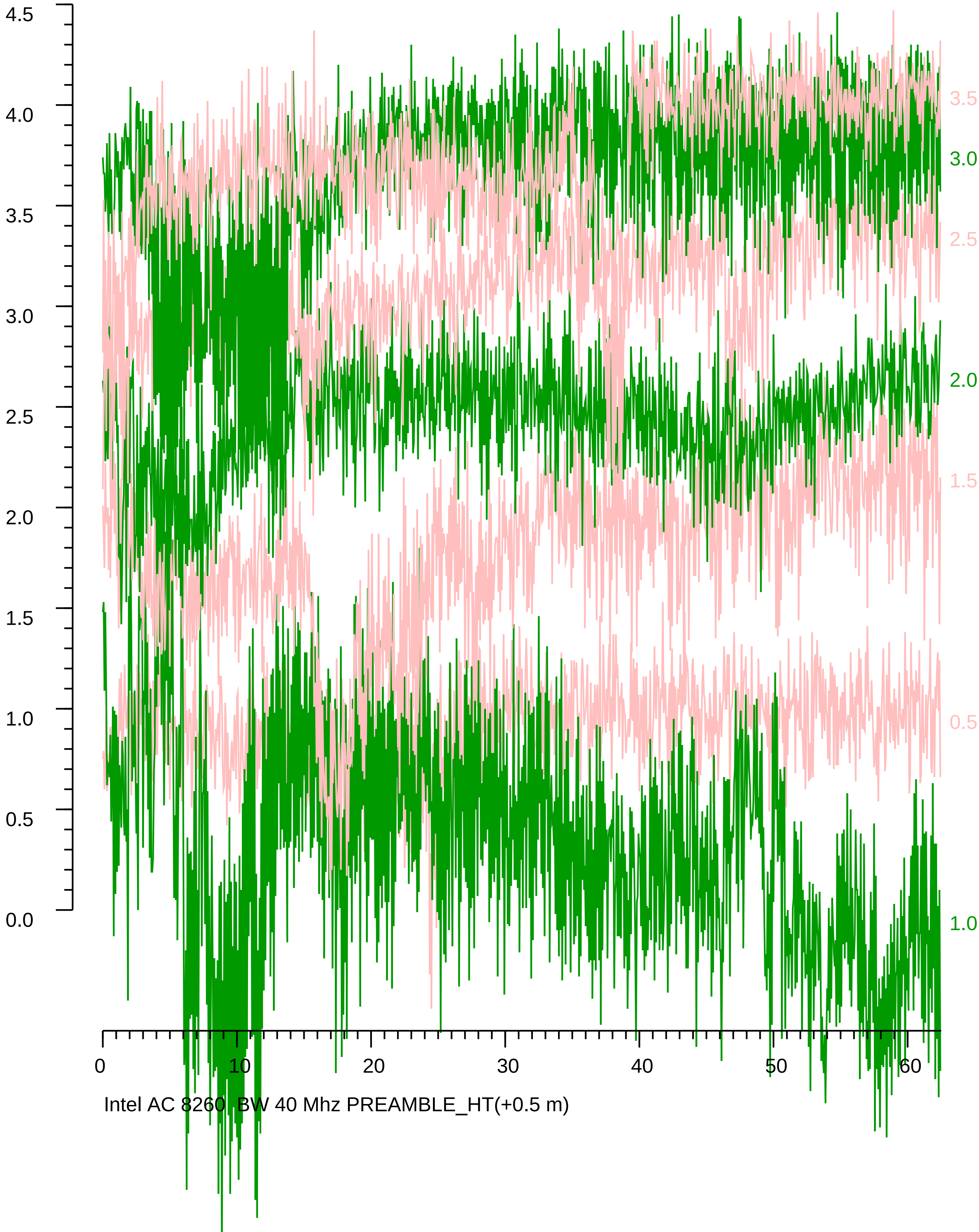
Red curve: expected -50 - 20 * log(R) dBm



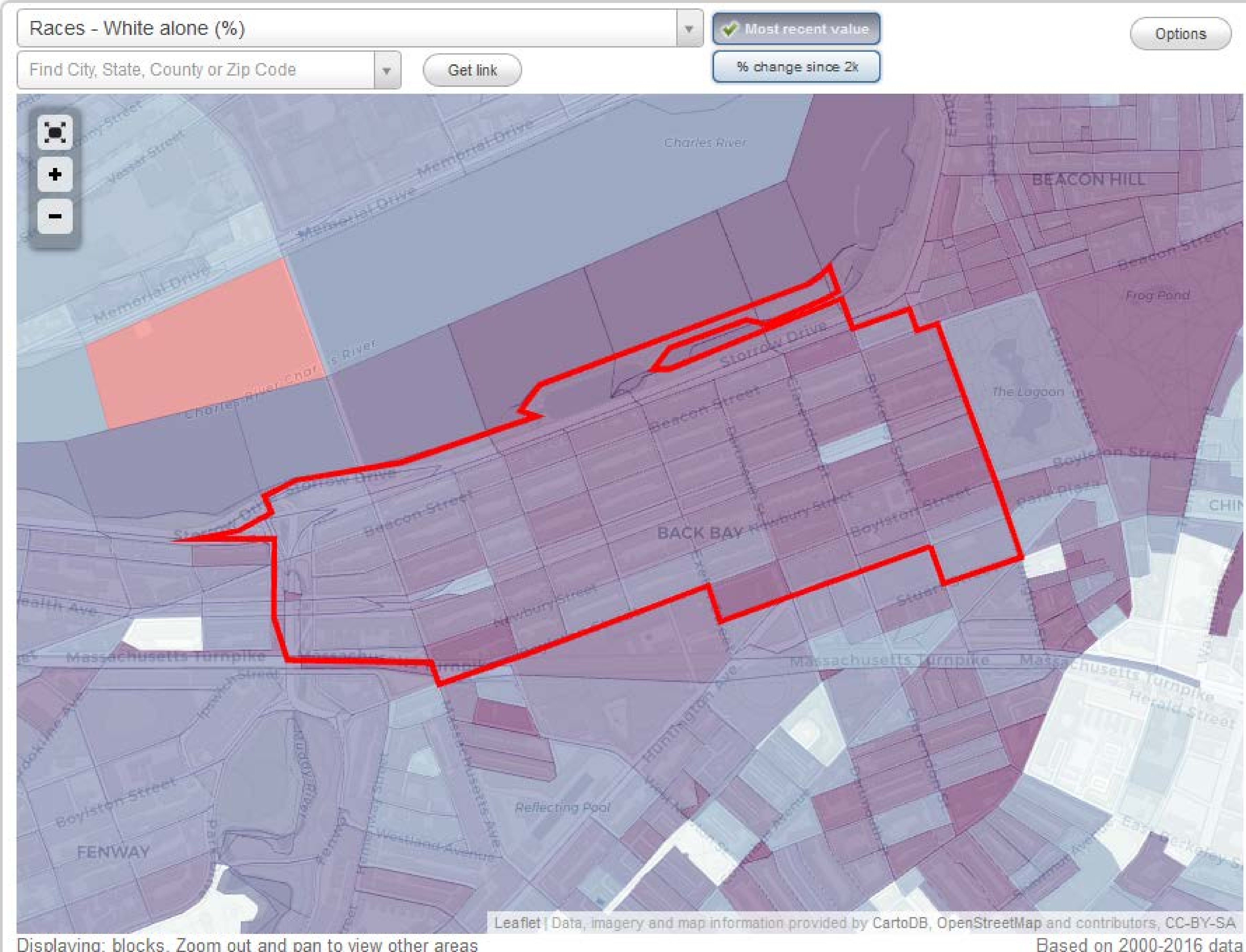
ASUS RT-ACRH13 BW 80 Mhz PREAMBLE_VHT



5.0
4.5
4.0
5.0
4.5
4.0
5.0
4.5
4.0
0
30
60
90
120
150
180
210
240
270
300
ASUS RT-ACRH13 BW 80 Mhz PREAMBLE_VHT



4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3.5
3.0
2.5
2.0
1.5
0.5
1.0
0
10
20
30
40
50
60
Intel AC 8260 BW 40 Mhz PREAMBLE_HT(+0.5 m)


Races - White alone (%)
Most recent value
% change since 2k
Options
Find City, State, County or Zip Code
Get link
Charles River
Memorial Drive
BEACON HILL
Beacon Street
Frog Pond
The Lagoon
Storrow Drive
Beacon Street
Boylston Street
Park Plaza
BACK BAY
Newbury Street
Massachusetts Turnpike
Huntington Ave
Herald Street
Reflecting Pool
FENWAY
Leaflet | Data, imagery and map information provided by CartoDB, OpenStreetMap and contributors, CC-BY-SA
Displaying: blocks. Zoom out and pan to view other areas
Based on 2000-2016 data