Smartphone battery consumption breakdown, and a possible approach to improve battery-life with cell-densification

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*: equal contribution

Talk Roadmap

- **Why should you care about smartphone battery consumption?**
- **What is consuming smartphone battery today and how much?**
- Role of distance and cellular network on the battery draw, cell densification
- Verification of ray-tracing model, and modem power experiments
- Do the findings generalize to phones/modems apart from Pixel 7A?
- Limitations and ongoing work

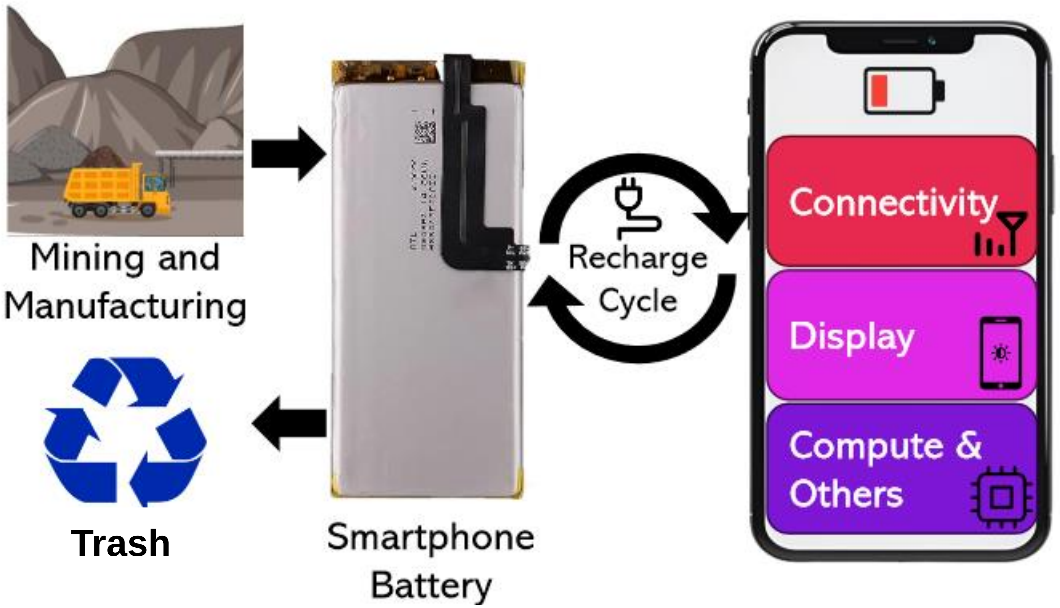
Why should you care about smartphone battery consumption?

- World Population today: 8.1 Billion (100%)
  Total num. of smartphones: 6.8 Billion (80%)

- With such large numbers, smartphones form highest contributor to embodied carbon footprint

- Among smartphones, larger part comes from batteries, which further can't be recycled

- Further, smartphones need to be charged on daily basis. New paper from Google [1] shows this also has a substantial environmental cost



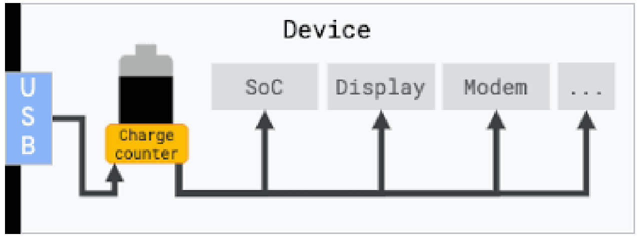
[1]: "**Energy and Emissions of Machine Learning on Smartphones vs. the Cloud" Communications of the ACM, Jan 2024**

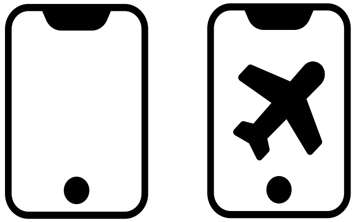
Past Work on Smartphone Battery Breakdown

- Studies done prior to 2020:
  "Display is the highest power consumption"

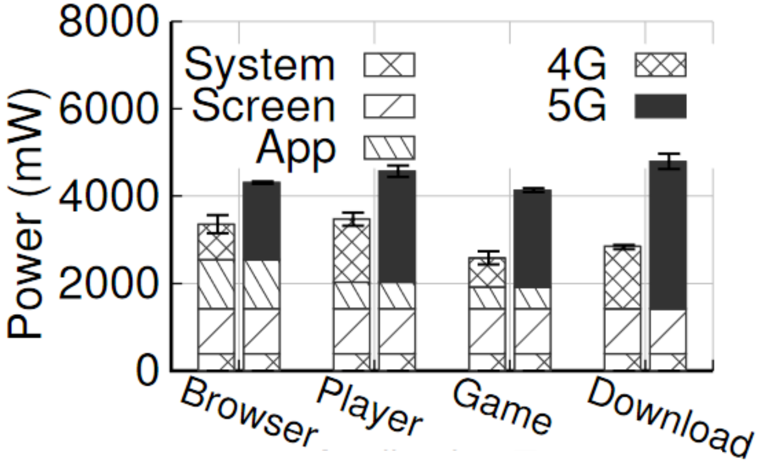
- What has changed?
  - 5G penetration
  - Increased uplink data behavior/zoom calls
  - Increased AI compute

- Measurement study in 2020, from BUPT China [2]
  - With 5G, modem starts dominating display
  - Indirect measurement, not validated?

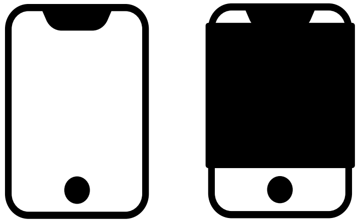




$P_{standby}$ - $P_{airplane}$



BUPT Measurements

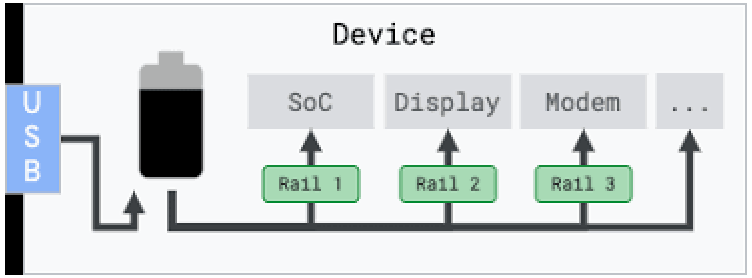


$P_{standby}$ – $P_{screen\text{-}off}$

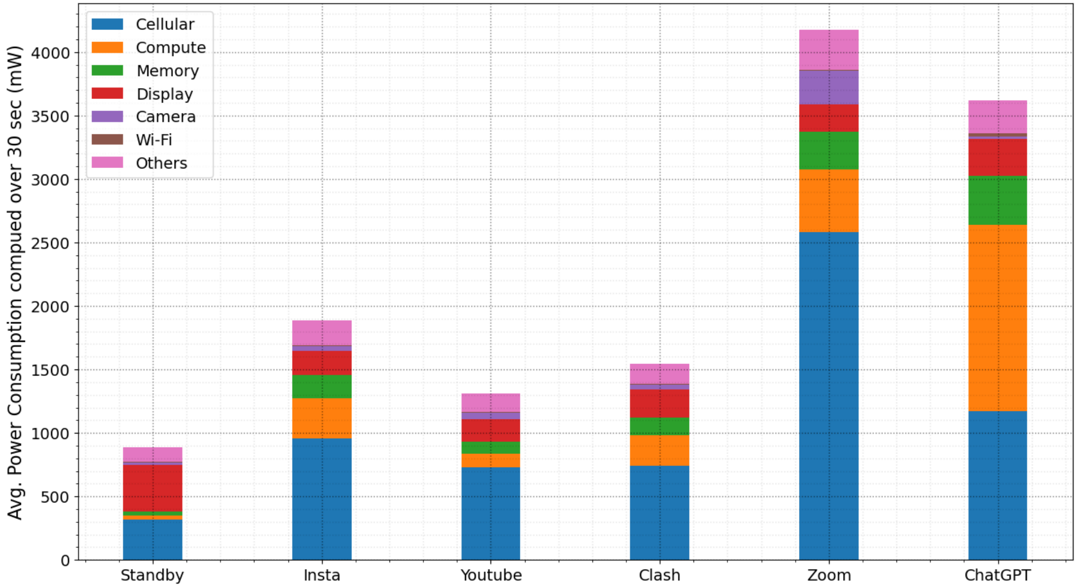
[2]: "**Understanding operational 5g: A first measurement study on its coverage, performance and energy consumption" Sigcomm 2020**

How have things changed now with improved tools?

- Google has introduced ODPM power rails on Pixels 6 and above (Nov. 2023)
- Allows fine-grained profiling, provides individual power consumption, runs as a background trace, doesn’t impact the user behavior.
- Collected data from multiple apps: Almost everywhere, cellular power dominates, unless we do a AI heavy task
    - Measured on a Pixel 7A smartphone
- Clearly, optimization of cellular power is of importance going ahead.



Google ODPM Power Rails



Cellular modem power is a silent battery killer today, as compared to display/compute

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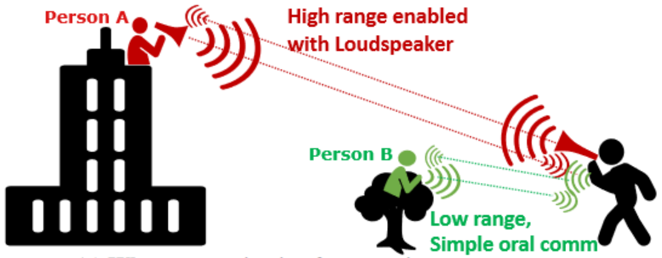
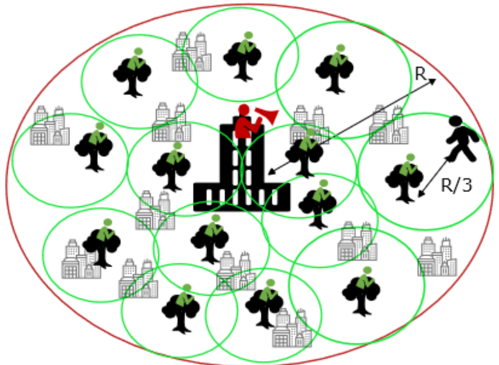
Hypothesis: Cellular Modem Power depends heavily on distance

Current Deployments
1. Sparse High Power Base Stations
2. Dedicated Tower Infrastructure
3. Located far from the users, increased battery draw on uplink

DensQuer Deployment
1. Multiple, Dense Low Power Base Stations
2. Reduced height, mount atop trees/street poles
3. Located close to users, improved battery life



(a) Why communicating far-away incurs more power

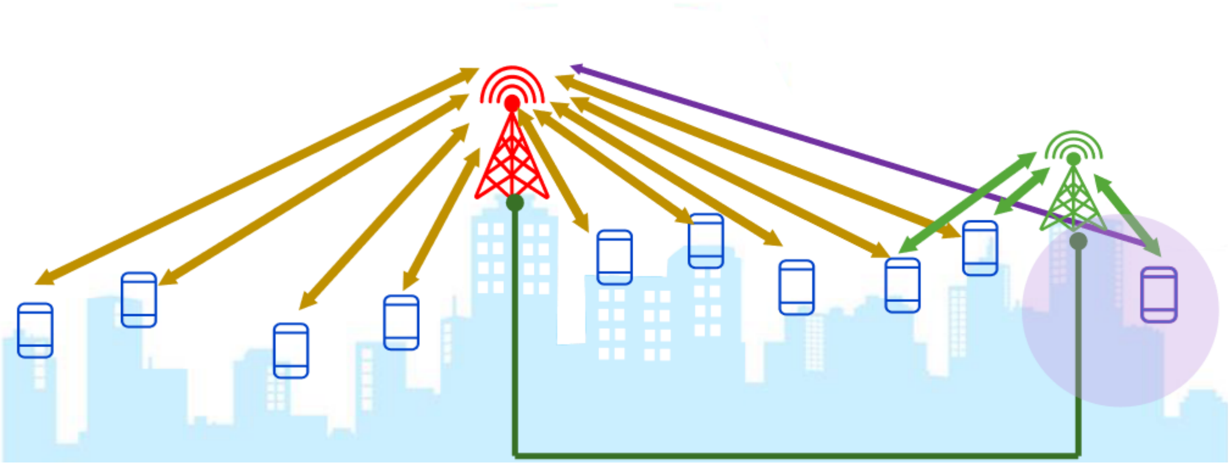


(b) How many Person B's do you need to cover the entire area of Person A?

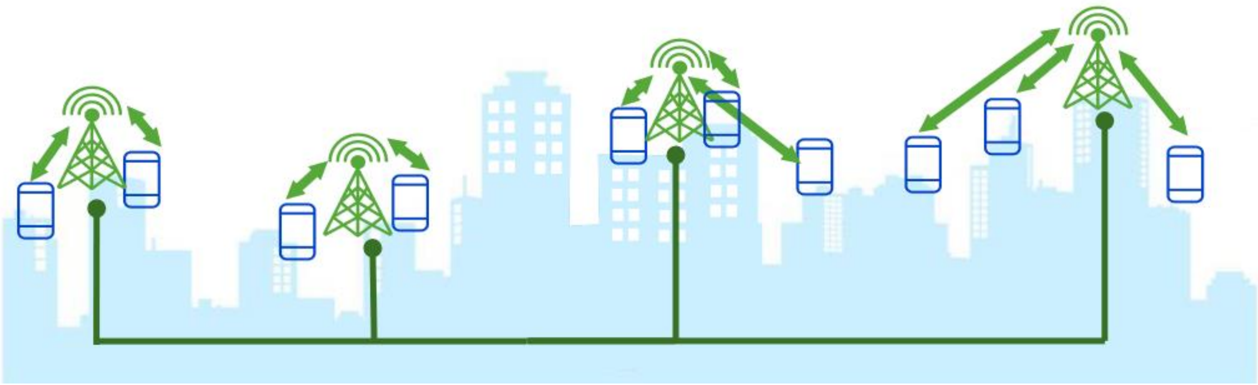
In a densified network, smartphone communicates to a closer located base-station, and thus we should see reduction in cell modem power. But how many smaller base-stations are needed to cover the entire area?

How does this differ from existing small-cell usecase?

Typically, small cells are used to increase capacity, or light up blind areas



We propose replacing the macro base-station with a network of smaller base-stations instead



How to create this network of smaller densified base-stations?

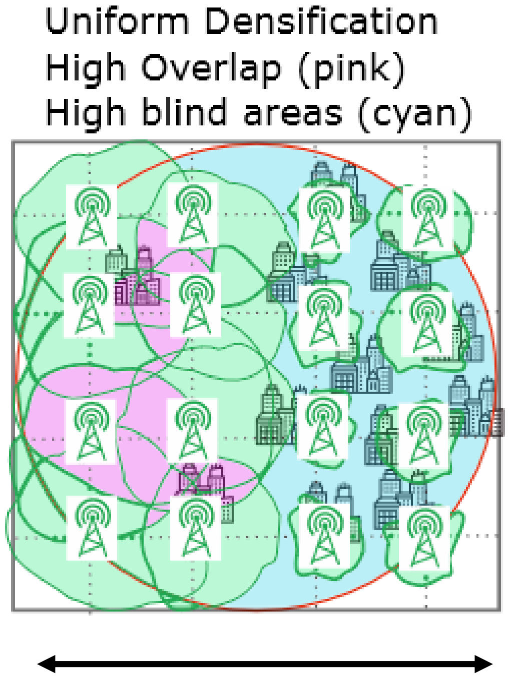
- **Typical approach, Uniform Densification:**
  - Utilize path-loss studies, compute the path loss exponent, and densify accordingly
  - Not optimal, require large number of base-stations, high overlap and blind areas

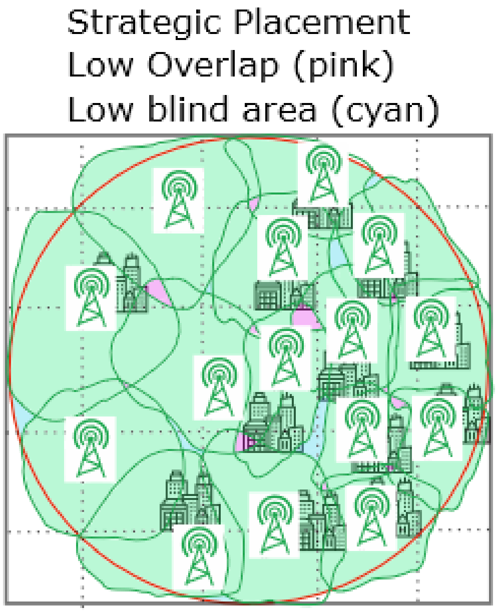
- **Suggested approach, Strategic placement:**
  - Optimization problem:

$$\min N$$
$$s.t. f(\{(x_i, y_i, h) | i = 1,2,..N\}) < target\ cov_{ratio}$$

  - Here, N is the total placed smaller base-stations f(.) takes a list of coordinates and determines coverage ratio wrt the macro cell. We set target cov_{ratio} = 70%
  - Analogous to sum of subset np-hard problem, no global provable optimum solution.
  - We attempt to solve the optimization via greedy algorithm, and as well as a randomized hill climbing heuristic

Goal is to cover a large macro base station area (red) with multiple smaller base-stations (green)





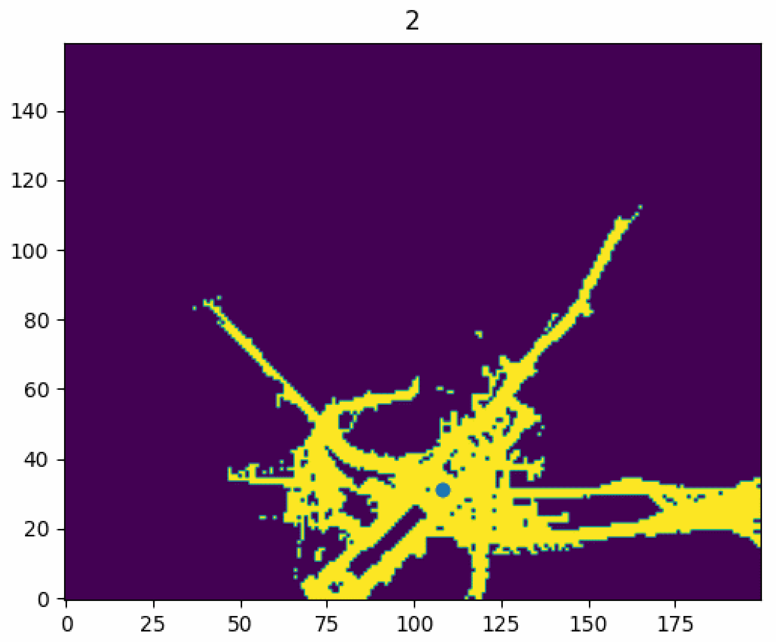
Divide the radius appropriately. R -> R/4

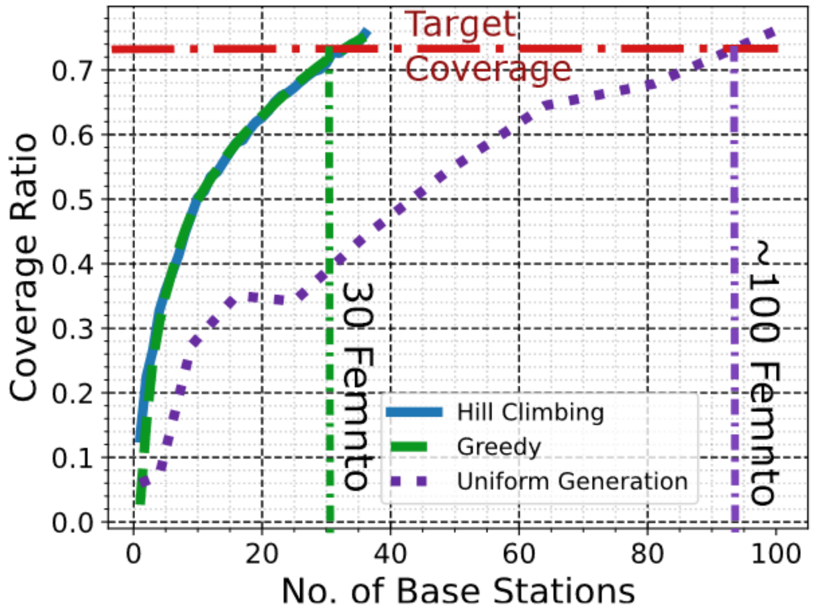
How to compute f(.)? Sionna computational framework does it efficiently and accurately. Greedy algorithm in action

- Greedy approach, chose the best position that gives highest coverage (first round), keep adding new coordinates greedily that incrementally bring the best added coverage

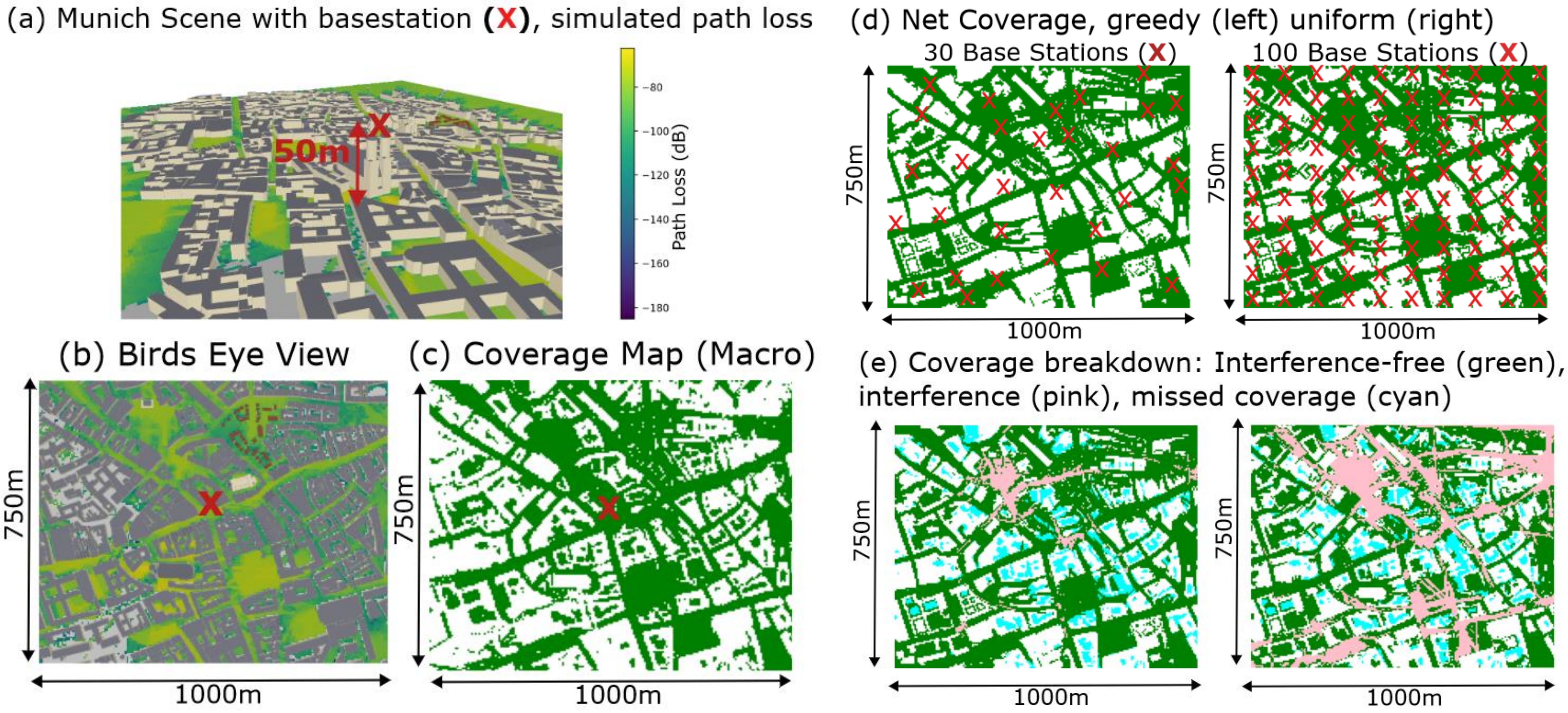
$$\max\left(f(\{(x_i, y_i, h)|i = 1,2,..N+1\}) - f(\{(x_i, y_i, h)|i = 1,2,..N\})\right),$$
$$stop\ if\ f(\{(x_i, y_i, h)|i = 1,2,..N+1\}) > target\ cov_{ratio}$$

- We also try a hill-climbing heuristic that allows randomized exploration to empirically see if greedy has performance hit

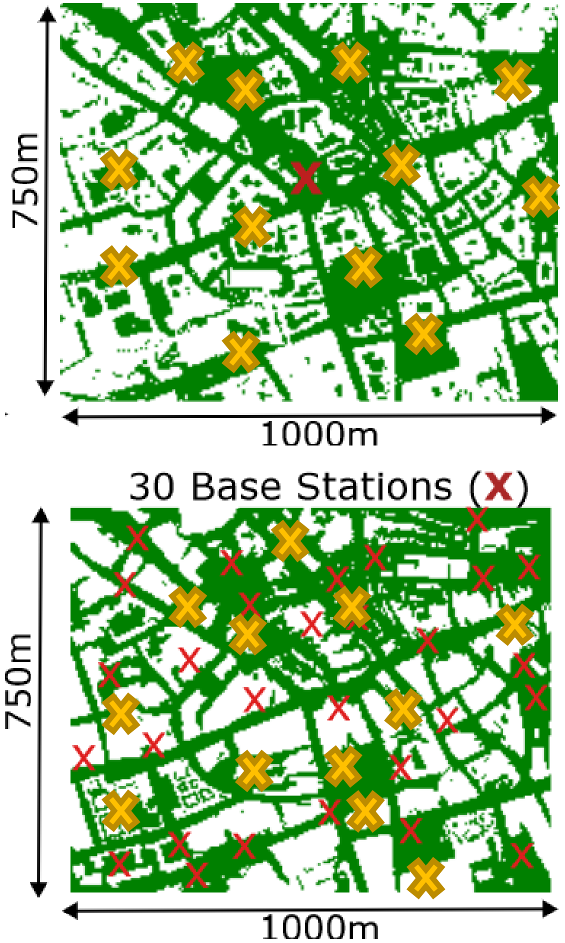


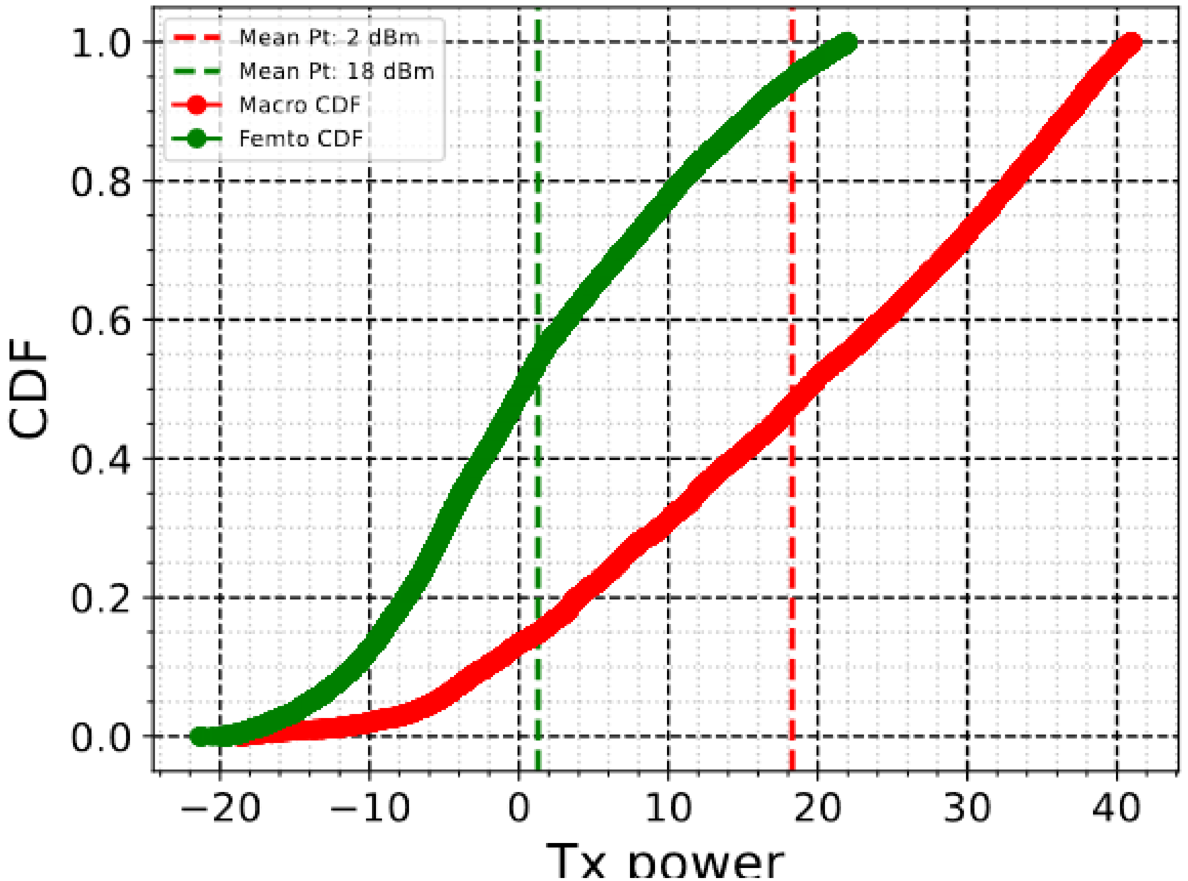


Visual comparison with/without strategic base station placement



How much transmit power would the users need in the dense network?





We have high power PAs (loudspeakers) but not low enough sensitivity (superhuman hearing) creating an imbalance

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Verification via real-world pathloss measurements

The ability of sionna to compute f(.) depends on closeness of it's path-loss calculations. Hence, we verify if the path loss in sionna agrees to an urban scenario by doing measurements in university

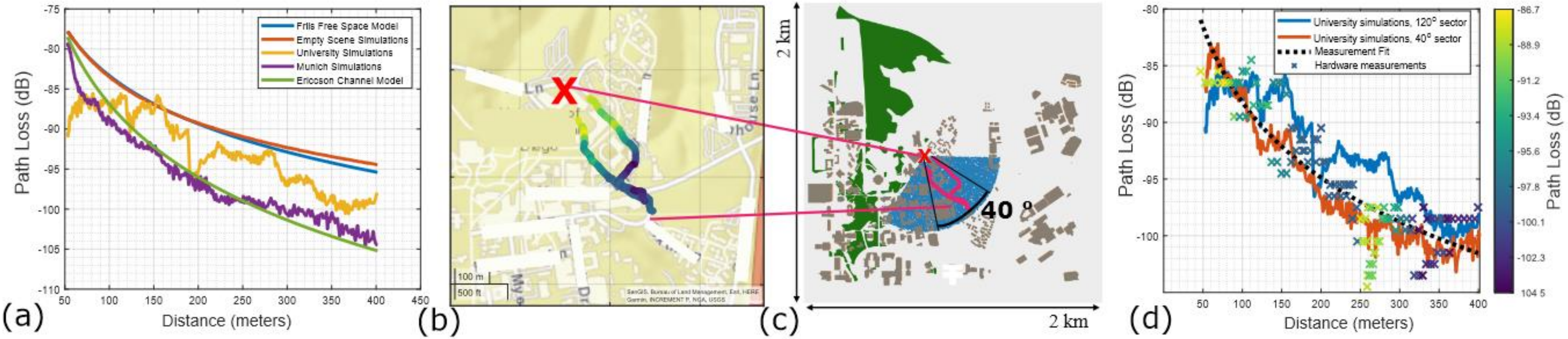
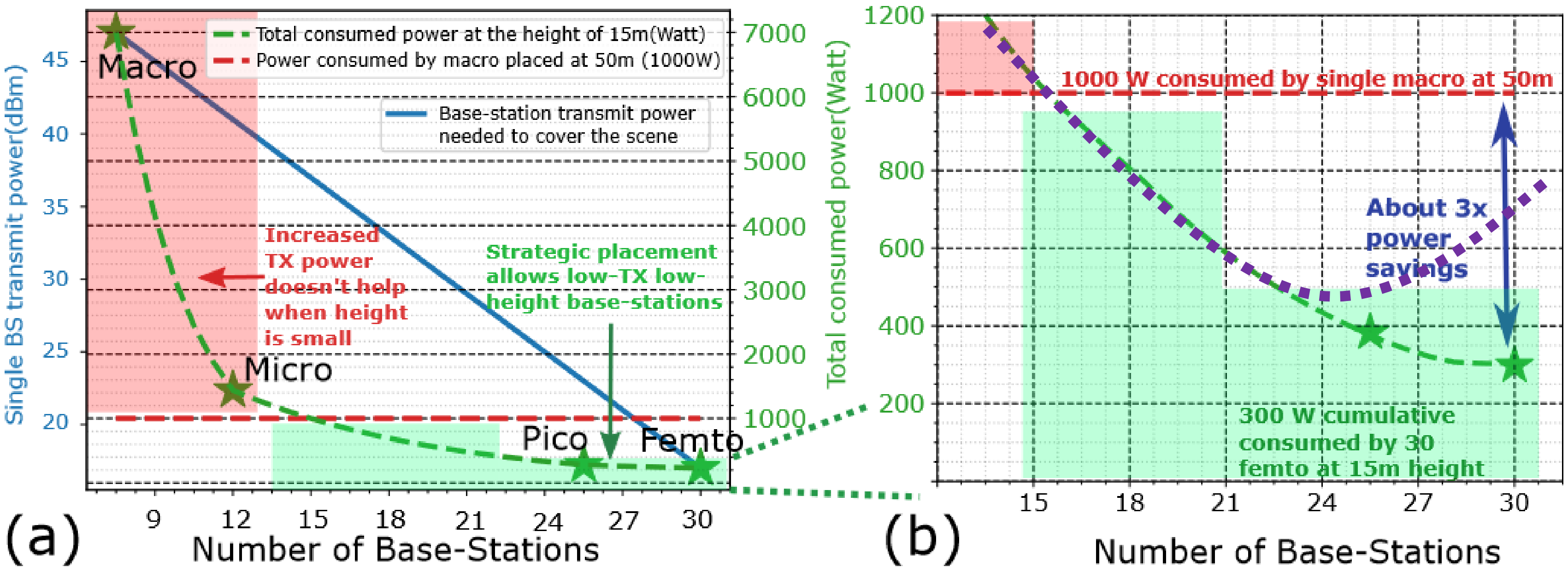
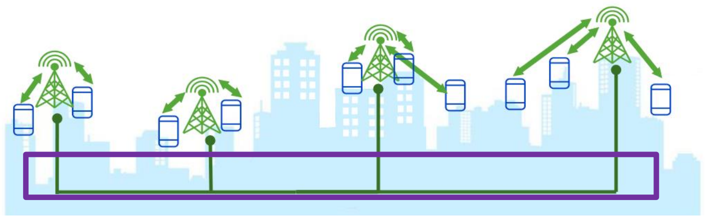


Figure 9: Sionna path loss benchmarking. (a) comparing simulated path loss with Friis Model and Ericcson channel model, (b) university path loss measurement setting, (c) sionna university simulation setup with varying sectors (120^o and 40^o) used for improving the computation (d) comparing university simulated path loss with real world measurement, where remarkably, sionna even predicts deep fades around 250m

Total network power consumption: Do sum of power consumption of the smaller base-stations exceed that of a single macro?

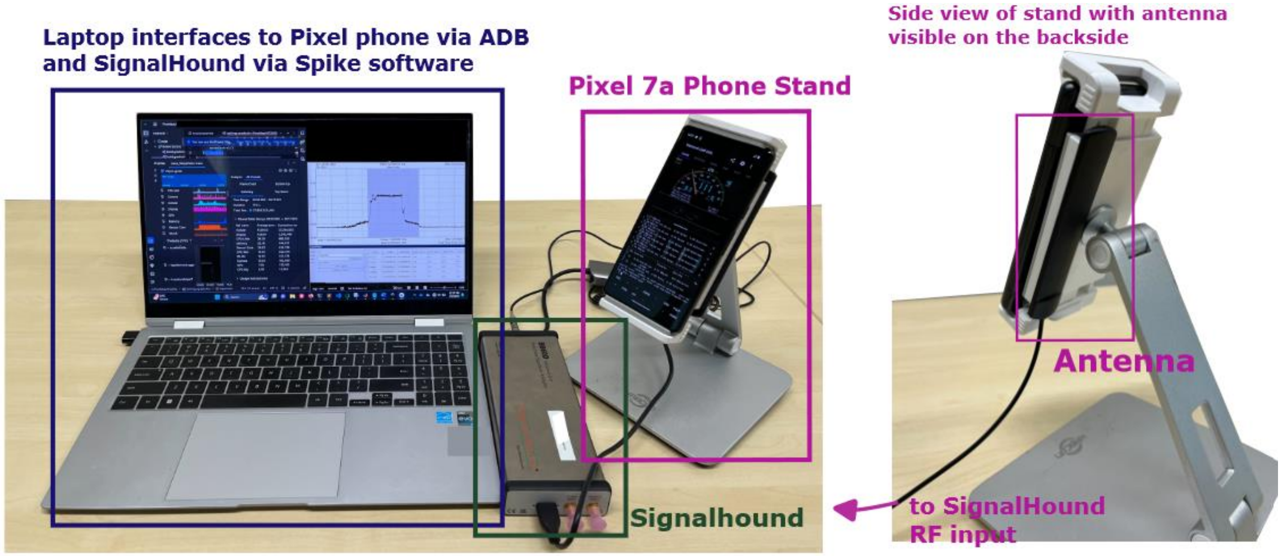
- We first reduce the height of all class of base-stations, and calculate greedily how many base-stations needed to get the equivalent coverage. Observe about 3x savings **(Caution)**
- Could not model the **network power correctly**. Existing theoretical models too simplistic to show up.

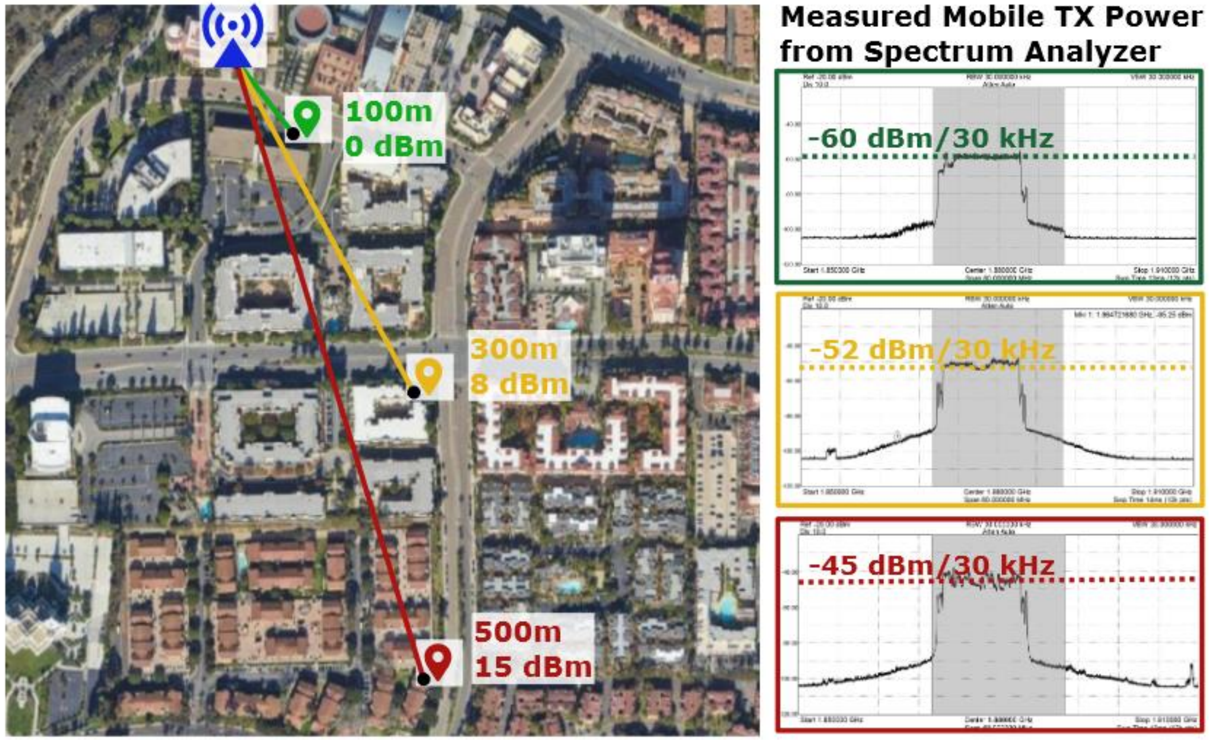




Experiment aim: how to translate the 15 dB UE transmit power reduction to real battery draw values in the phone?

- We can get cellular power consumption from Pixel 7A
- Created a setup with Signalhound Spectral Analyzer to measure phone's TX power levels
- Moved farther from a base-station until we see 15 dBm increase in TX power





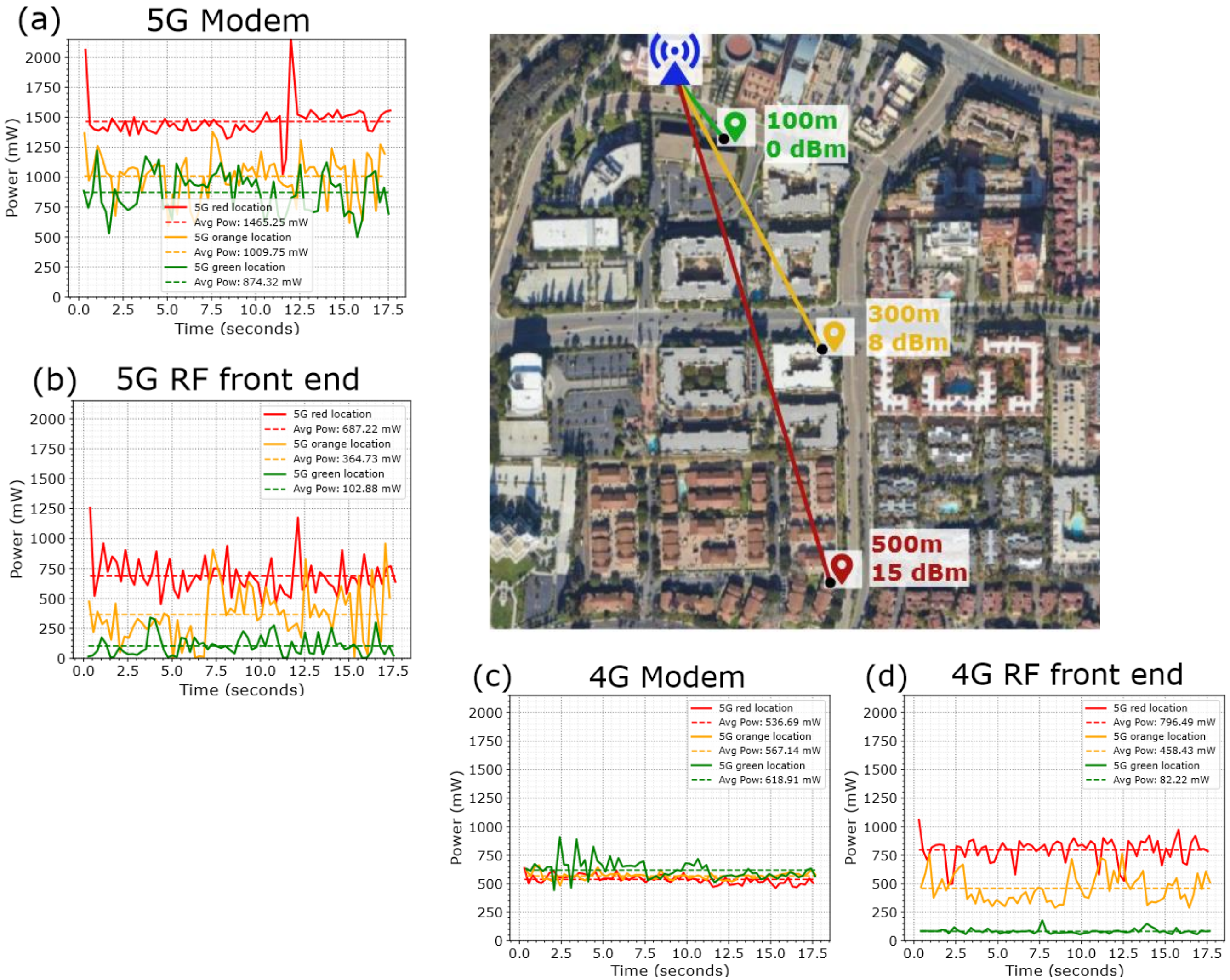
Experiment 1: Uplink Power Consumption of 5G/4G with distance

- **Experiment Setting:**
  Commercial Base Station (T-Mobile), Band 78
  Collected data at three locations (green, yellow, red, roughly 100-300-500m away) while performing a fixed 5 Mbps Iperf uplink transmission

- **Results:**

  - **RF Front End Power Consumption:** Increases in both 4G and 5G as a consequence of TX pow

  - **Modem Power Consumption:** Doesn't increase in 4G (makes sense), but shows an unusual increases in 5G at the red location.
    <u>Need more granular data collection</u>



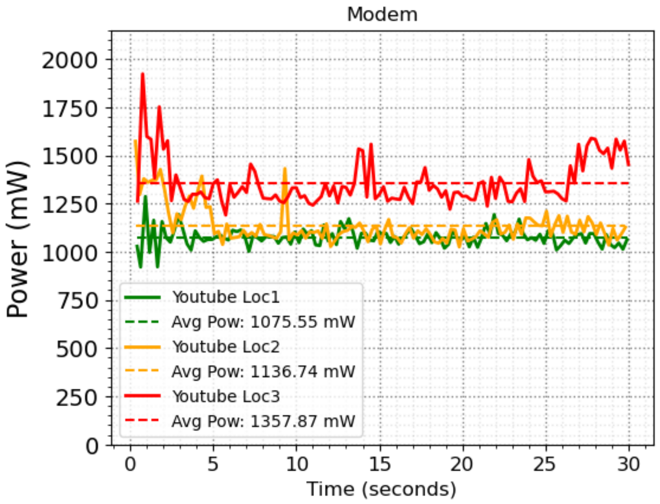
Experiment 2: Downlink Power Consumption of 5G with distance

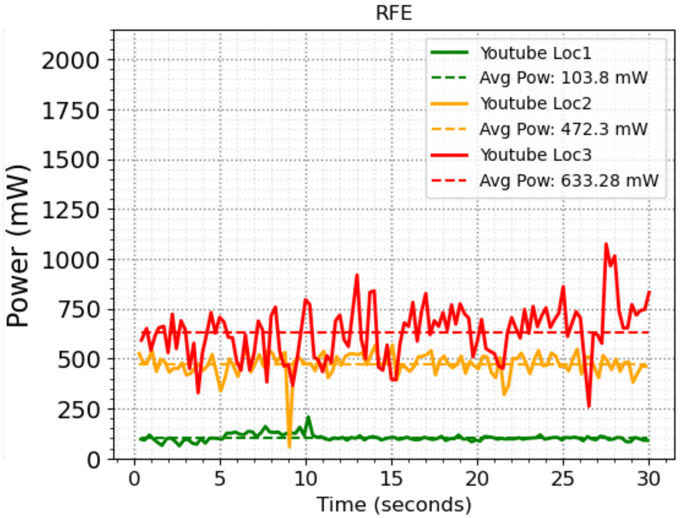
- **Experiment Setting:**
  Commercial Base Station (T-Mobile), Band 78
  Collected data at three locations (green, yellow, red, roughly 100-300-500m away) while watching 1080p youtube over 5G modem

- **Results:**

  - **RF Front End Power Consumption:** Increases with distance, LNA power? If yes, it is not negligible as traditionally perceived in papers

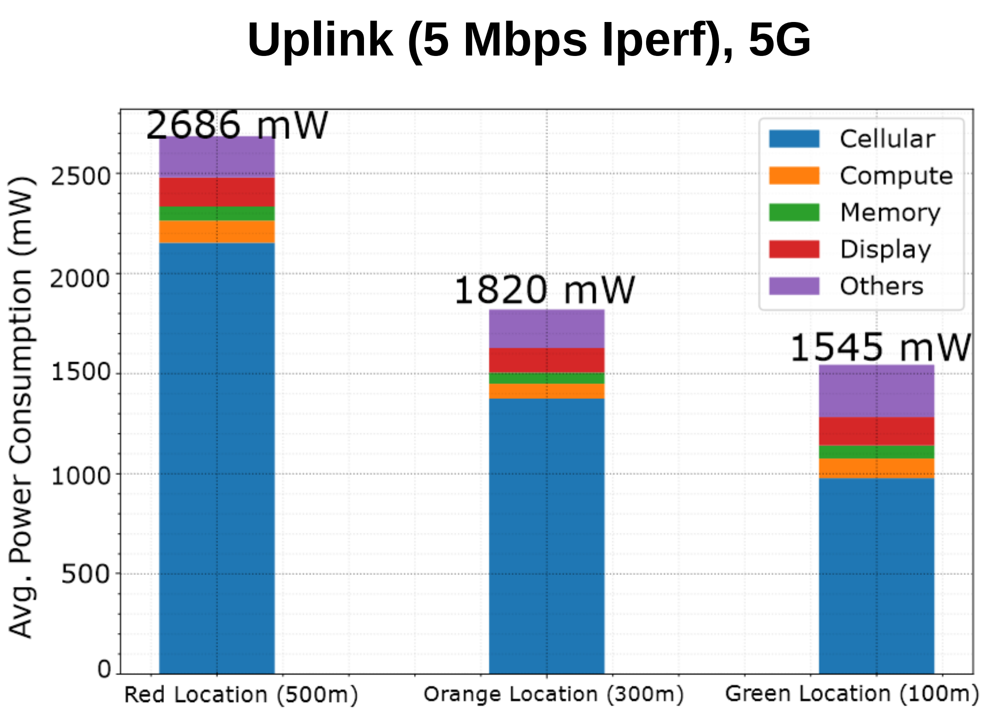
  - **Modem Power Consumption:** Still increases with distance, although we are not sure why (need further experiments)

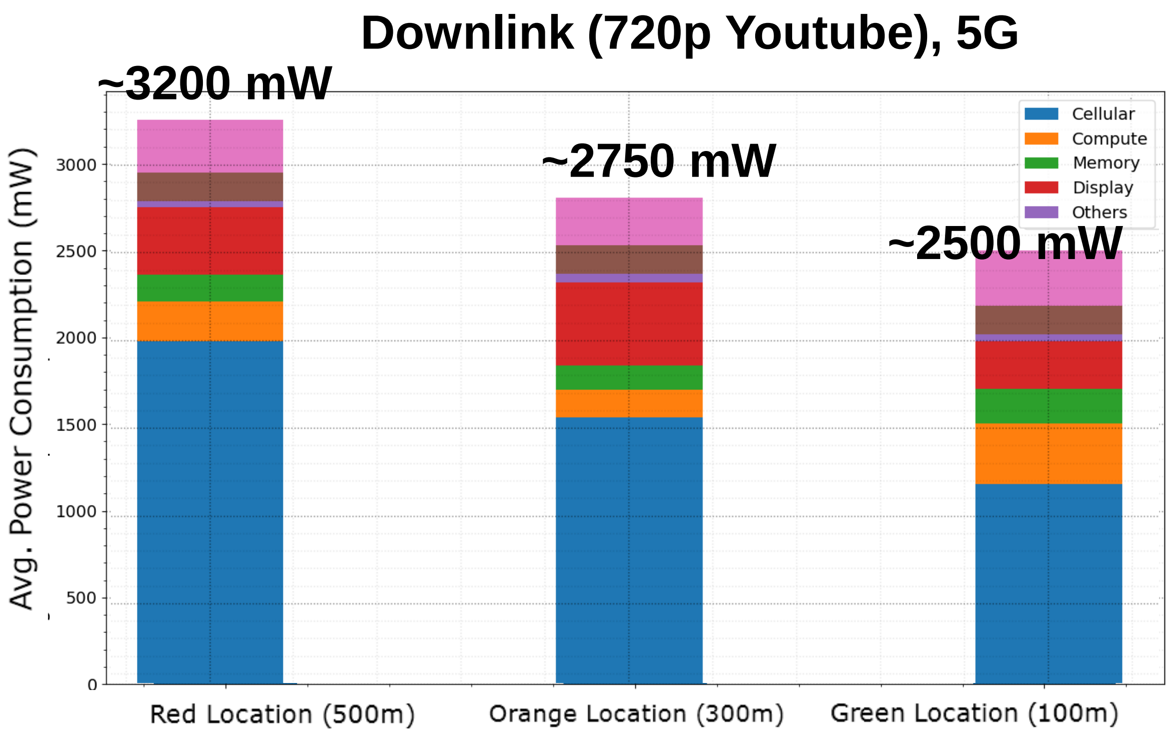




Battery consumption versus distance, uplink and downlink

- **Overall Battery:** Including other components, power draw is 40% reduced at green location (uplink consumption) and reduces by 22% reduced at green location (downlink consumption)



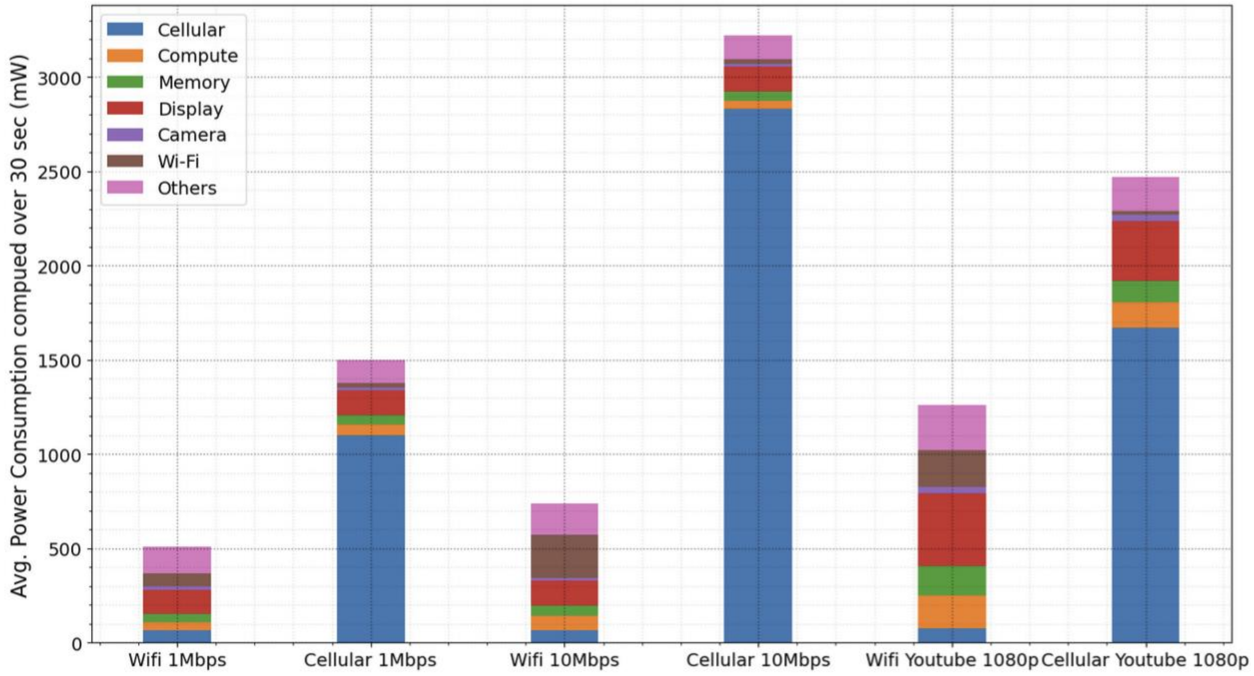


Experiment 3: Comparison between Wi-Fi and 5G (Downlink only)

- **Is there any fundamental power consumption due to Mbps data movement? Then Wi-Fi power consumption will be high.**

- **Experiment Setting:**
  srsRAN base station (in-lab, indoor base station, center freq. 3.5 GHz) connected to Pixel 7A phone, to do a controlled downlink experiment (1 Mbps, 10 Mbps iperf downlink), as well as 1080p youtube. Comparison is with Wi-Fi in our lab (UCSD WiFi)

- **Results:**
  Compared to even a controlled indoor base-station, that handles just one client, and a WiFi hotspot handling multiple clients, even then at the smartphone the power measurements reveal that cellular power consumption overshadow anything else (including a 1080p HD on display), but Wi-Fi measurements are much more comparable



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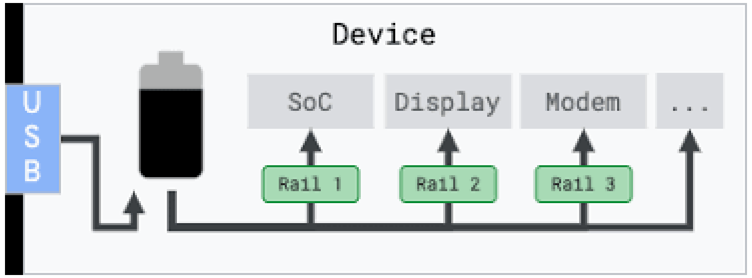
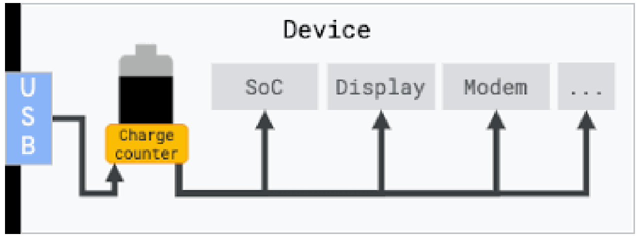
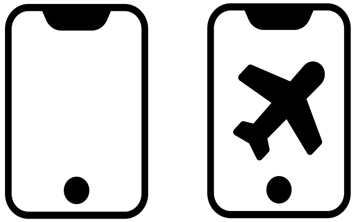
  (Does cellular power dominate even for newer phones? Comparison with wifi/display?)
- Limitations and ongoing work

Recall Slide: Past Work on Smartphone Battery Breakdown

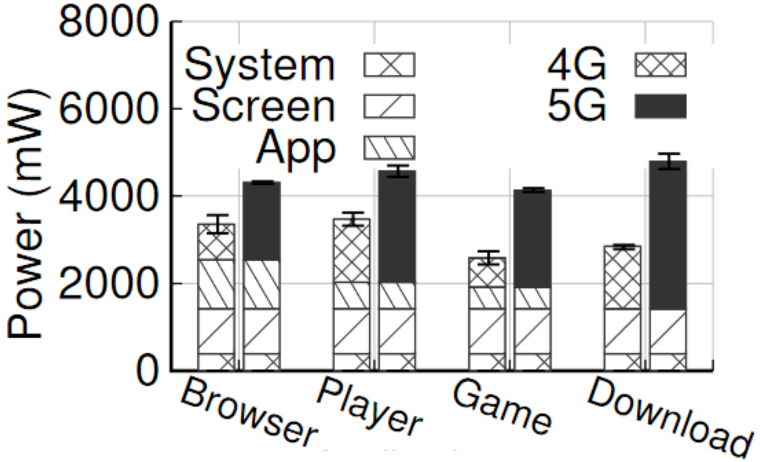
- Studies done prior to 2020: Display is the highest power consumption [2-4]
- What has changed from 2020?
  - 5G penetration
  - Increased uplink data behavior/zoom calls
  - Increased AI compute?
- Measurement study in 2021, from BUPT China
  - With 5G, modem starts dominating display
  - **Indirect measurement, not validated?**



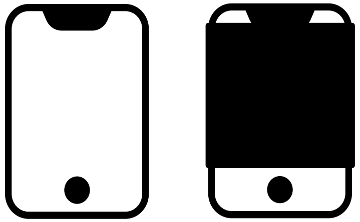




$P_{standby}$ - $P_{airplane}$



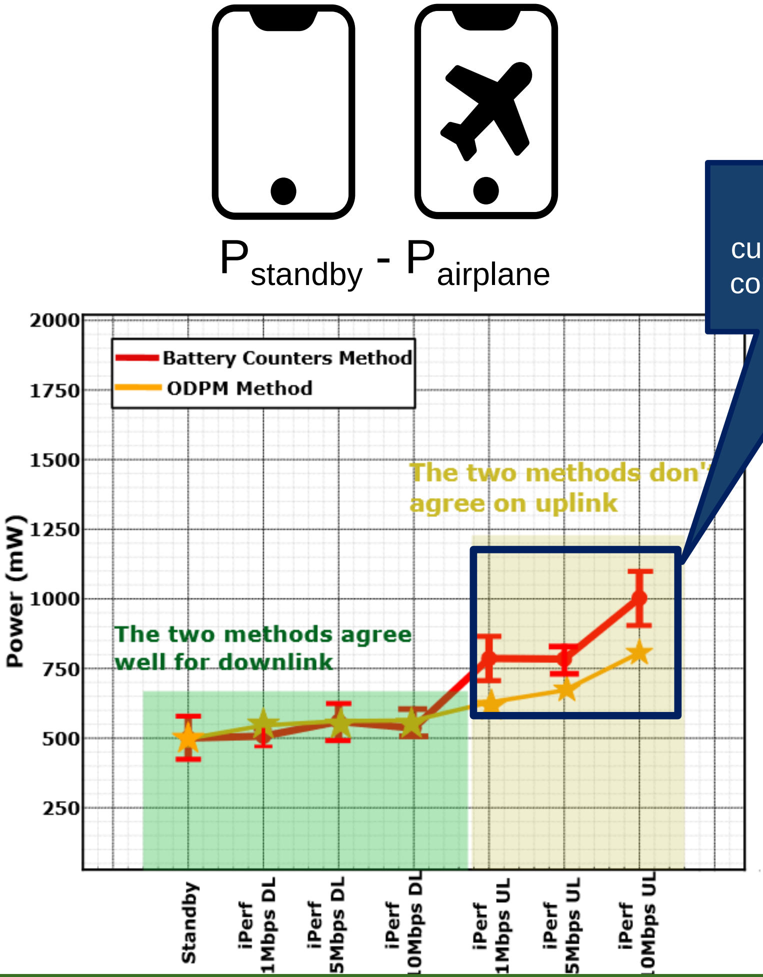
BUPT Measurements



$P_{standby}$ – $P_{screen\text{-}off}$

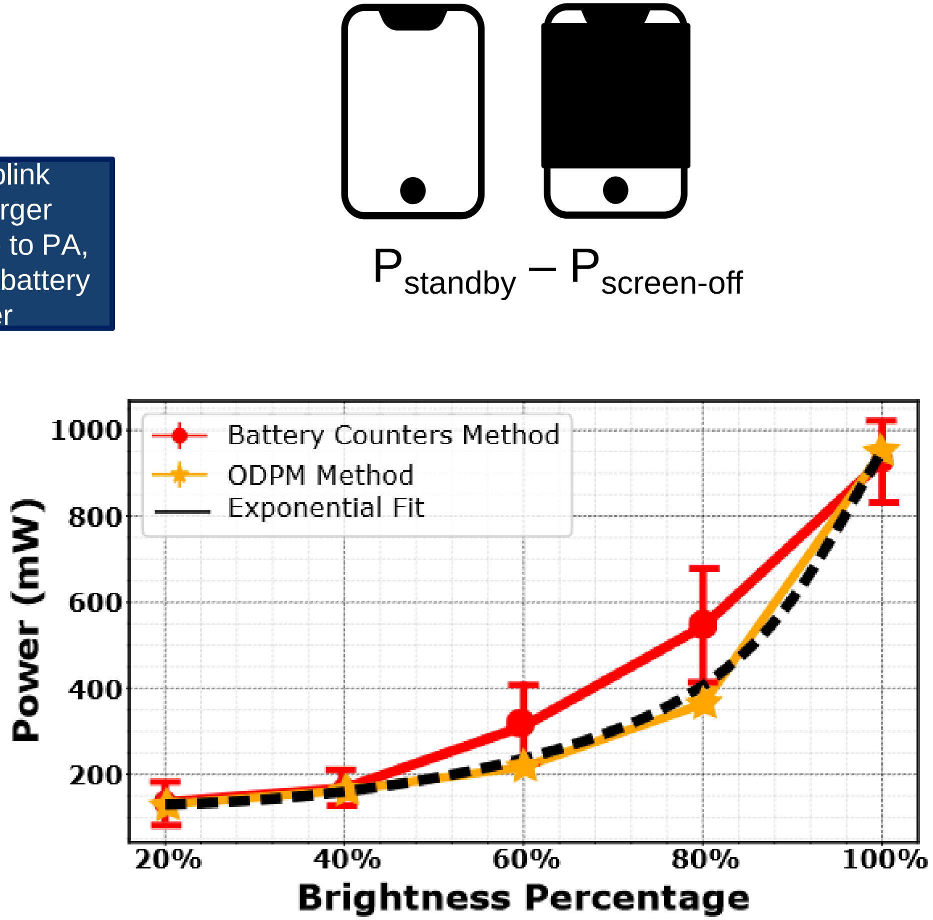
Validating the past background suppression work with ODPM baseline on Pixel 7A: Decent estimates of display/downlink power

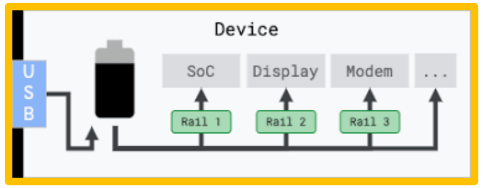
$P_{standby} - P_{airplane}$

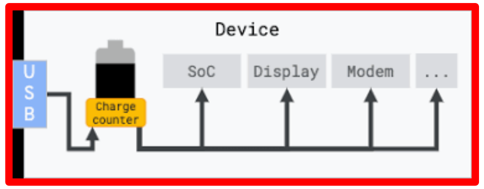


Maybe uplink causes larger currents due to PA, corrupts the battery counter

$P_{standby} – P_{screen\text{-}off}$



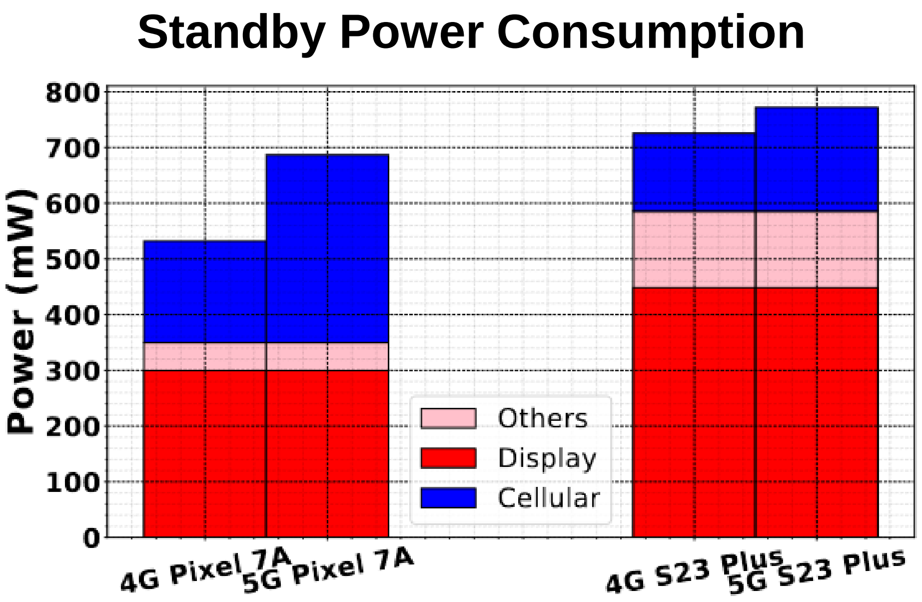


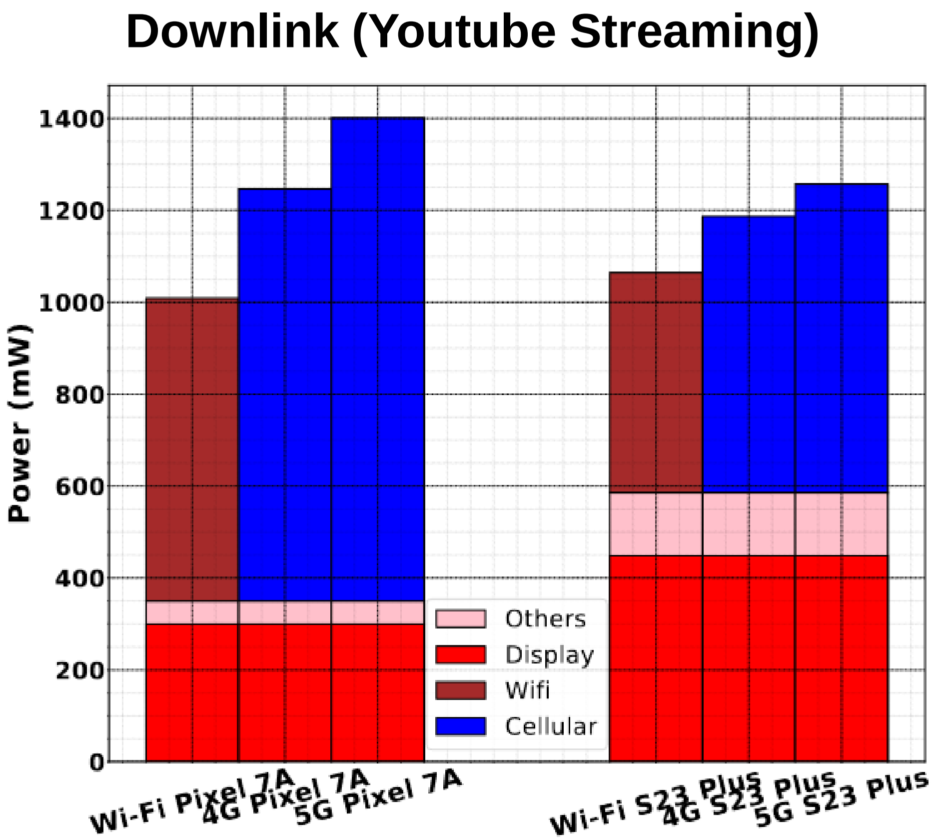


Gives us a method which we can apply to other phones and estimate cellular/display power (at a trend level at least)

Does the trend hold for S23+, with latest Qcomm modem/better screen?

Pixel A has Exynos 5300,
S23+ has Qualcomm X70





These should be correct at a trend level, however there is room for improved data collection

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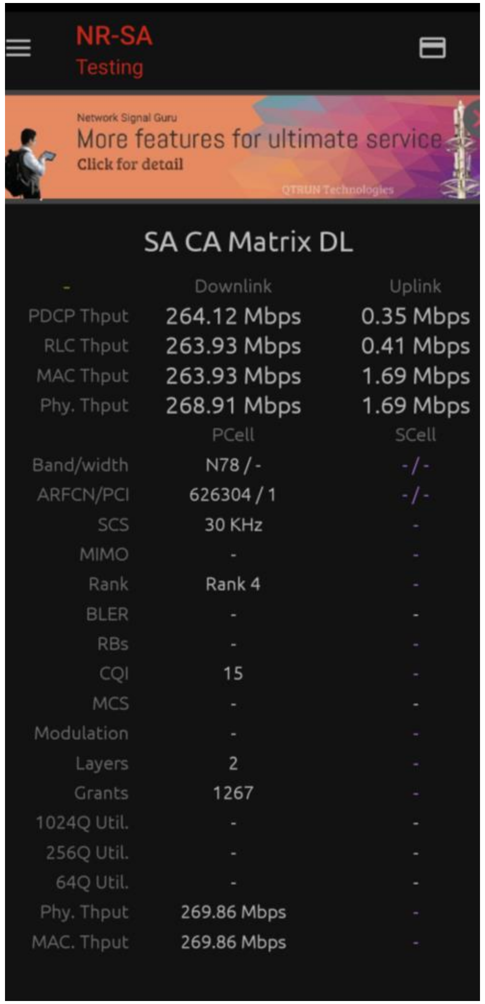
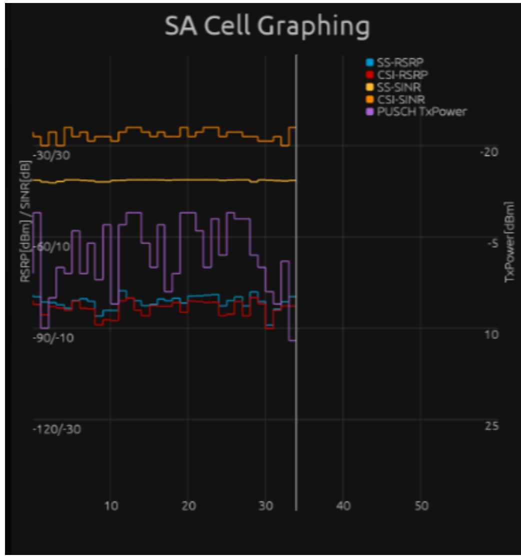
  (Does cellular power dominate even for newer phones? Comparison with wifi/display?)
- **Limitations and ongoing work**

Possible improvements to the Ray-tracing framework, data collection

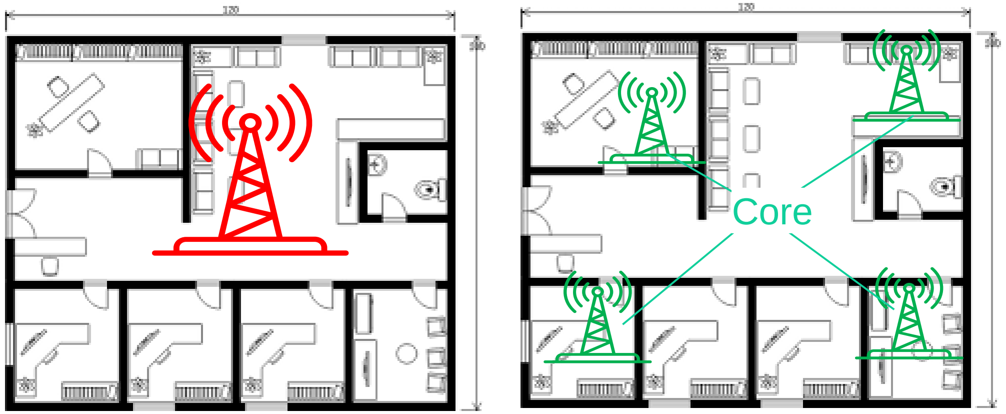
- **Limitations of Ray-tracing framework:** Sionna doesn't model indoor areas, at the time did not have terrain elevation maps
- **Lack of MIMO modelling:** We have so far considered base-stations only with a single antenna. The assumption was to work with EIRP, so it doesn't matter on the number of antennas for Tx. However, MIMO can enable more strategic placements, and capability to handle interference
- **Theoretically provable greedy algorithm:** There are hints that the greedy might be optimal/close to optimal since hill-climbing performs similar. Possibility of some proofs?
- **More detailed data logging at UE**: With rooted phones, we later realized TX power is available directly, as well as MIMO logs (however, not for all networks).





Ongoing work: Indoor test-bed creation, protocol optimization

- Creating an indoor test-bed to realize other issues like mobility/handover in the dense network, working with network layer researchers in university
- Improved data collection pipeline, and interference studies. Extending power studies to 5G RedCap nodes, and day-long ODPM traces to profile the user dependence on cellular
- <u>Protocol explorations</u>, what can be done to reduce power at modem. Something like a 5G-LE (BLE) low energy variant? <u>Absolutely needed to enable connectivity on the go</u>
  (Can explore a potential collaboration!)



UC San Diego
JACOBS SCHOOL OF ENGINEERING
Electrical and Computer Engineering

WCSNG
Wireless Communications Sensing and Networking

Thank you!

Email: agg003@ucsd.edu

(Arxiv pre-print: https://arxiv.org/html/2403.13611v1)