# On the Effectiveness of Secret Key Extraction from Wireless Signal Strength in Real Environments

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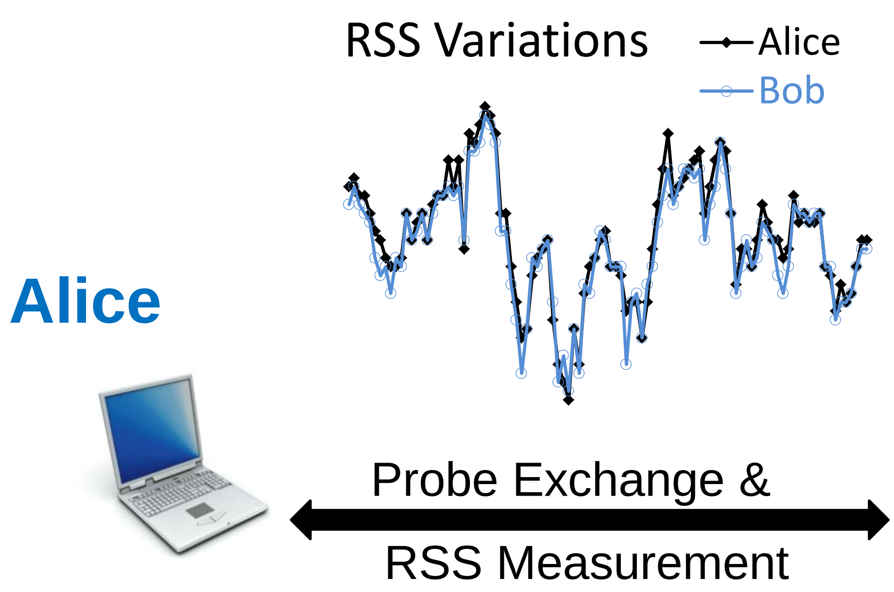
# Problem Definition

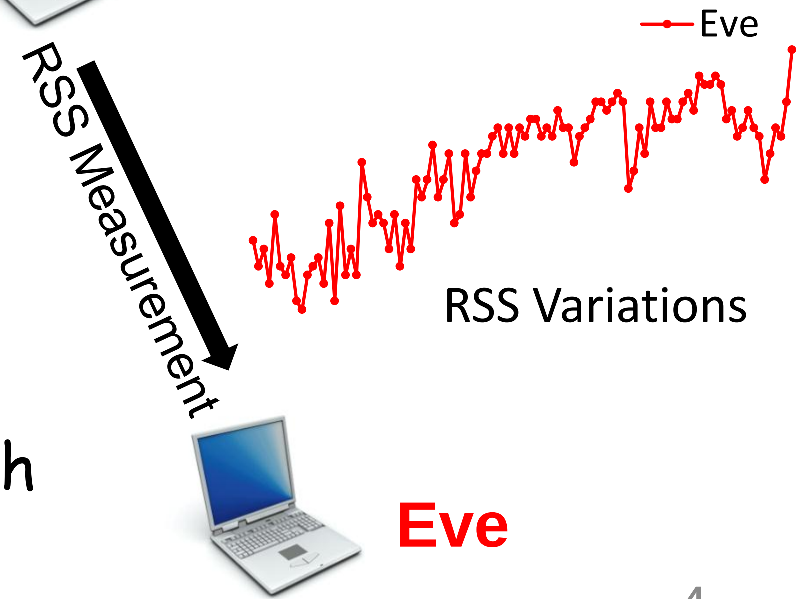
- wireless nodes, Alice & Bob, need to share secret key
- concerns with public key cryptography
- quantum cryptography – too expensive
- less expensive solution - use inherent randomness in wireless channel to extract secret key bits

# Wireless Channel Characteristics

- measured reciprocally at Alice, Bob
- when away by more than few multiples of wavelength, Eve cannot measure same channel
- channel varies with time

# Use of Received Signal Strength (RSS)




- Alice, Bob expected to see "*identical*" RSS variations [Stutzman '82]
- realistically, they must deal with lack of perfect reciprocity

# Related Work

Mathur '08, Li '06, Aono '05

- extract single bit per measurement
- experimental results from limited indoor settings
- Alice, Bob do not communicate to handle mismatches

  **will result in key disagreement in large number of cases**

Azimi-Sadjadi '07

- suggested using 2 stages from quantum cryptography - information reconciliation, privacy amplification
- did not implement!

# Our Contributions

- adaptive key extraction
  **increases secret bit rate 4-fold**
- implement information reconciliation to handle bit mismatch
- implement privacy amplification to reduce correlation between successive bits
- through extensive real world measurements, identify settings (un)suitable for key extraction
- expose new predictable channel attack in static settings

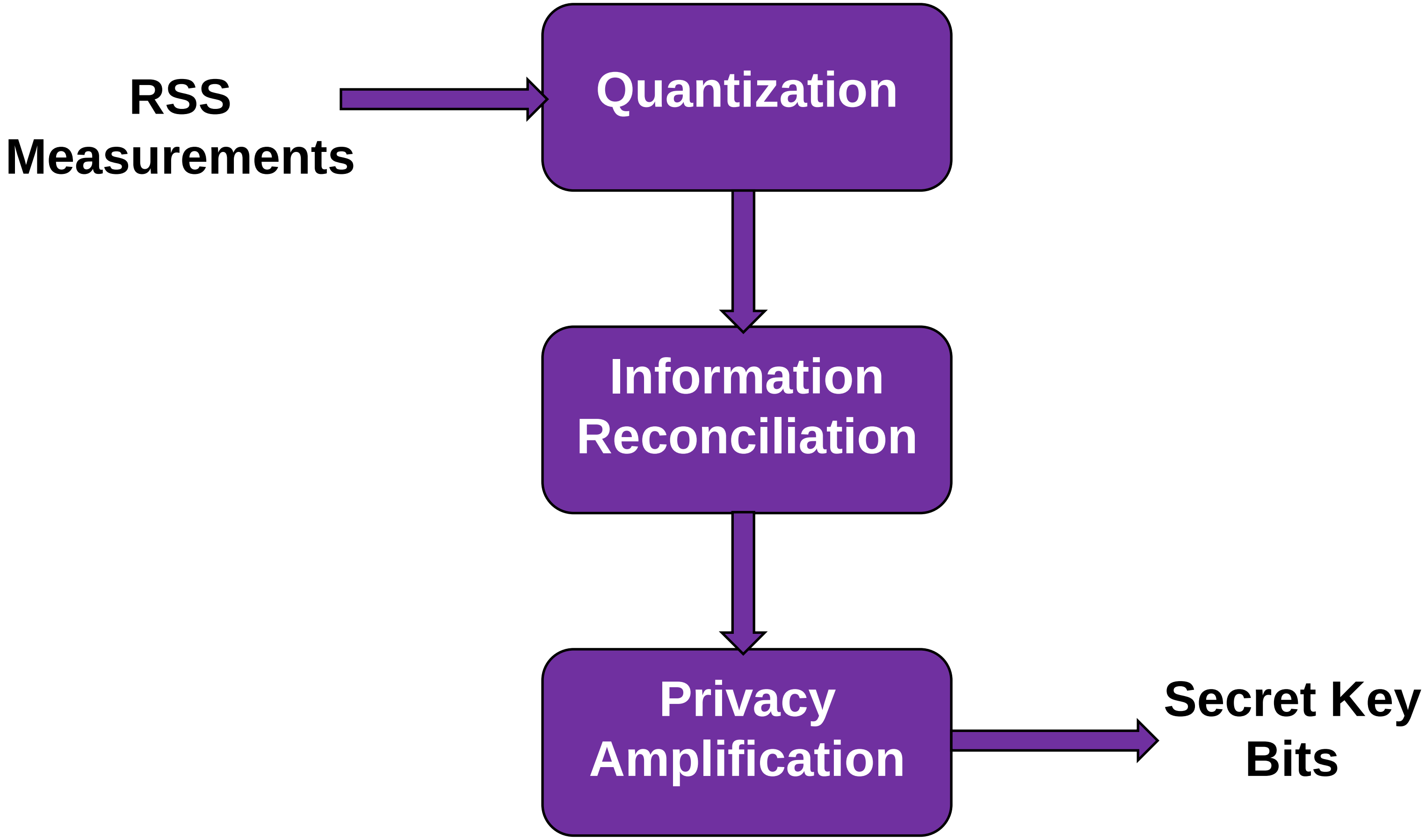
# Overview

- adversary model
- secret key extraction
- real world measurements, results
- summary

# Adversary Model

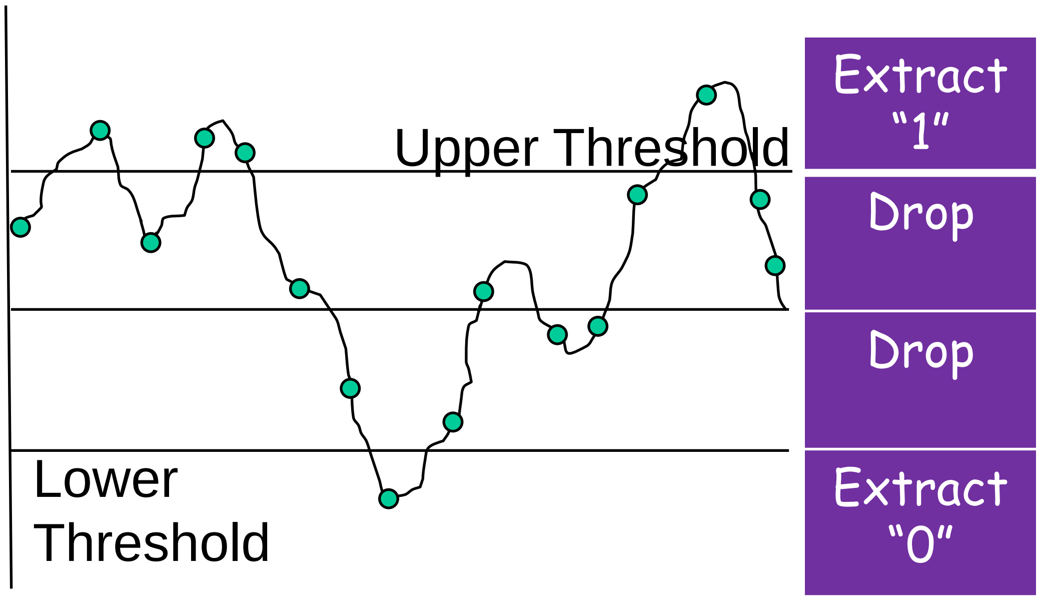
- adversary Eve
  - listens to all communication between Alice, Bob
  - can measure channel between herself and Alice, Bob
  - separated from both parties by distance >> wavelength
- Eve not interested in disrupting communication between Alice, Bob
- Alice, Bob are not authenticated

# Secret Bit Extraction



# Adaptive Quantization

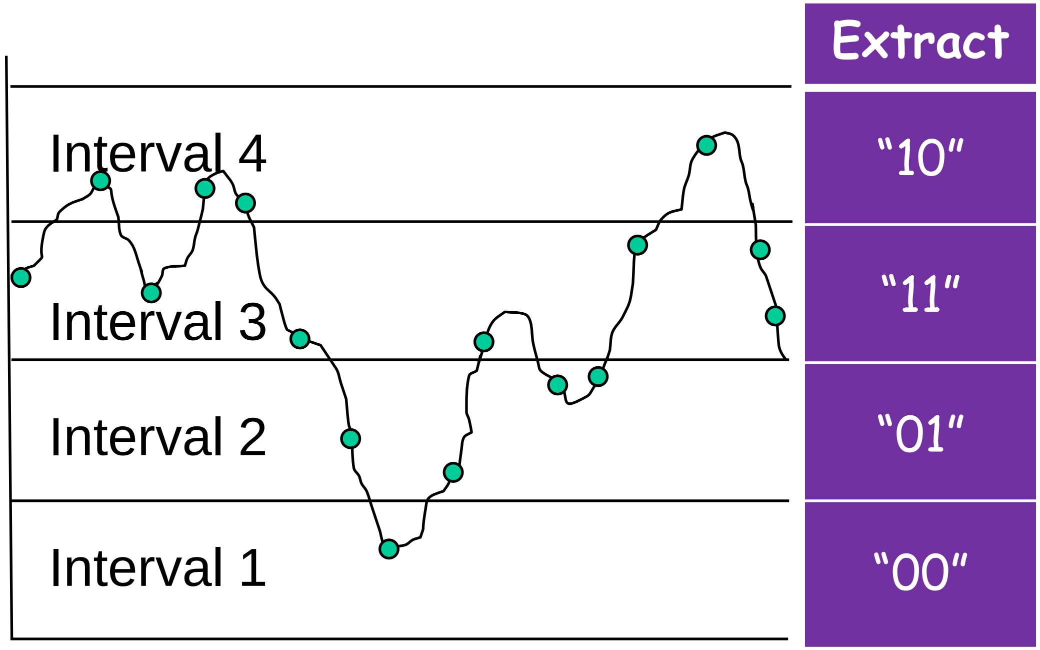
how to generate bits from RSS measurements?




adapt threshold for small blocks of measurements

Extracted Bits – 1 1 1 0 1 …

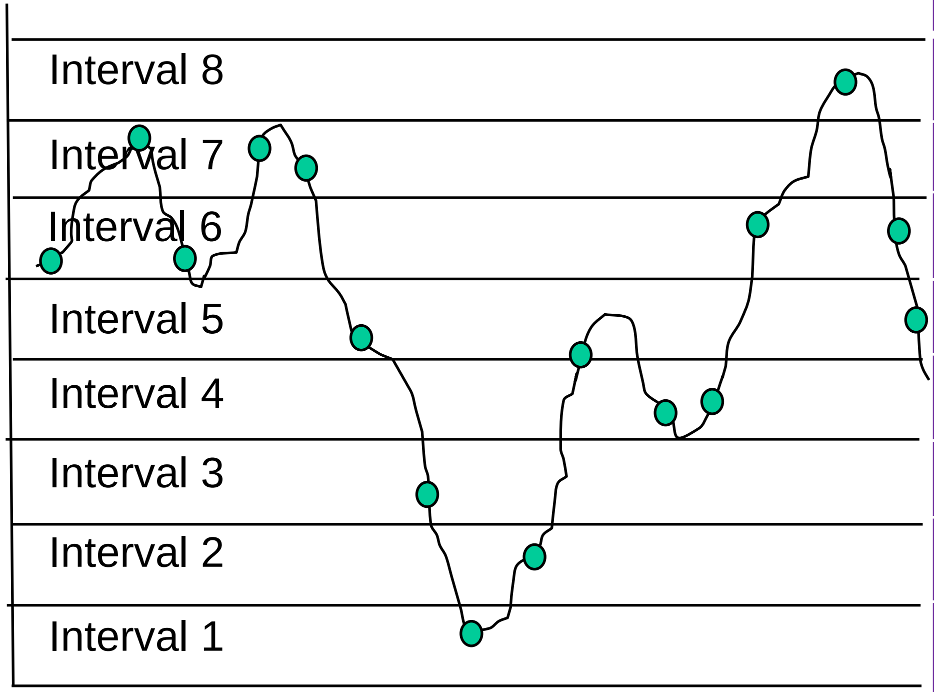
# Adaptive Quantization




adapt # intervals depending on range

Extracted Bits - 11 10 11 10 10 11 01 00 01 …

# Adaptive Quantization




| Extract |
|---|
| "111" |
| "110" |
| "101" |
| "100" |
| "011" |
| "010" |
| "001" |
| "000" |

adapt #intervals depending on range

limit: N ≤ log [Range]

Extracted Bits - 101 110 101 110 110 100 010 …

Adaptive Secret Bit Generation (ASBG)

# Information Reconciliation [Brassard '06]

differences in between bit streams of Alice, Bob arise due to

- noise/interference, wireless hardware limitations
- half-duplex nature of channel

solution:

- exchange parity information of small blocks of bits
- locate, correct mismatches using binary search
- permute, iterate until probability [success] > threshold

# Privacy Amplification [Impagliazzo '89]

- short-term correlation between subsequent bits when probing rate > $(\text{coherence time})^{-1}$
- need to remove bits leaked during information reconciliation
- solution:
  - apply 2-universal hash function h: {1…M} → {1…m}
  - for inputs x, y, probability [h(x) = h(y)] upper bounded by 1/m
  - decreases output length, but increases entropy

# Implementation

laptops - Alice, Bob

- equipped with Intel PRO/Wireless 3945 ABG cards
- monitor mode for collecting RSS measurements
- use *ipwraw* driver for raw packet injection

probes – IEEE 802.11g beacon frames

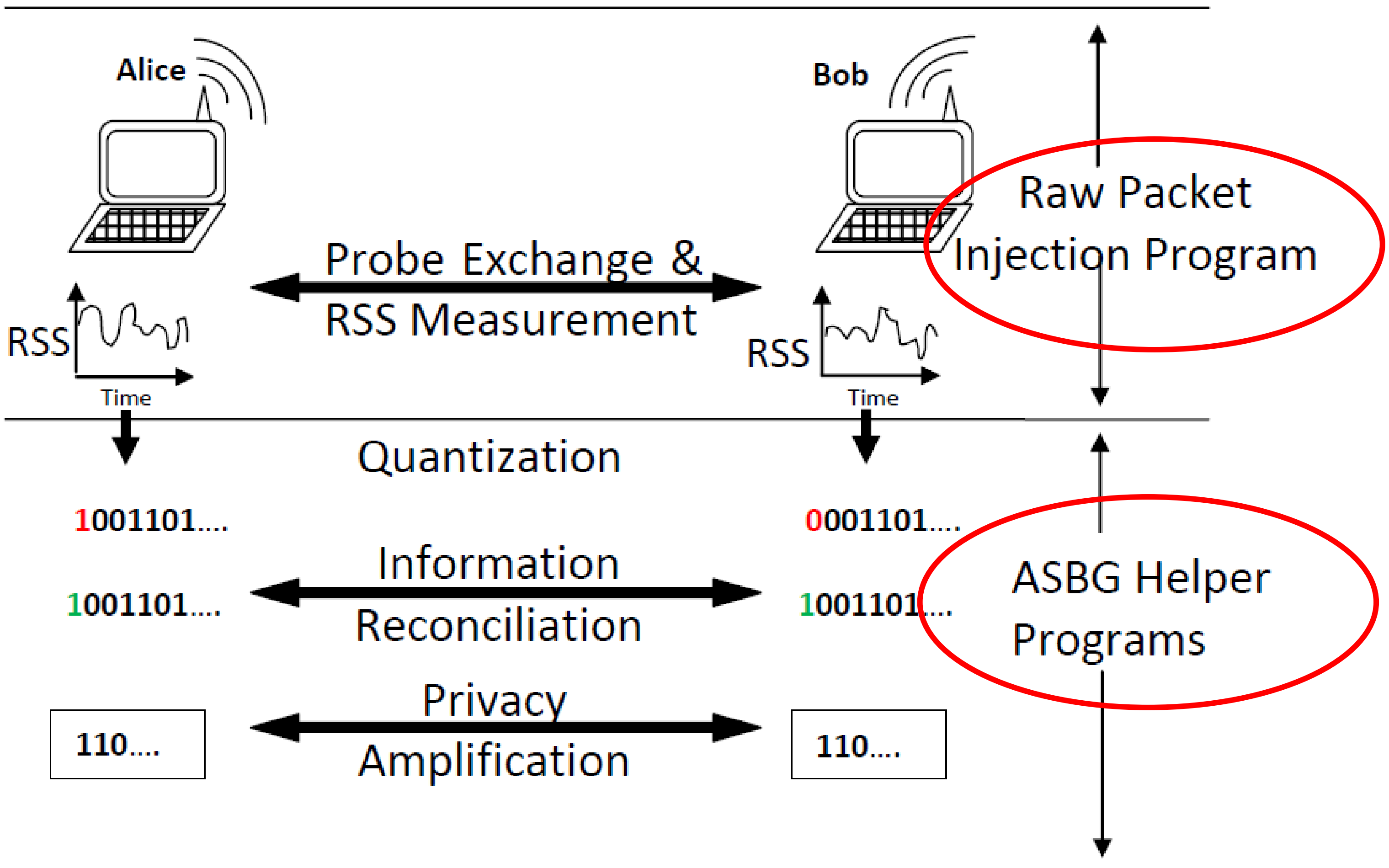
- management frames prioritized over data frames
- allows better control over probing rate
- probing rate ~20 packets per second

# Implementation

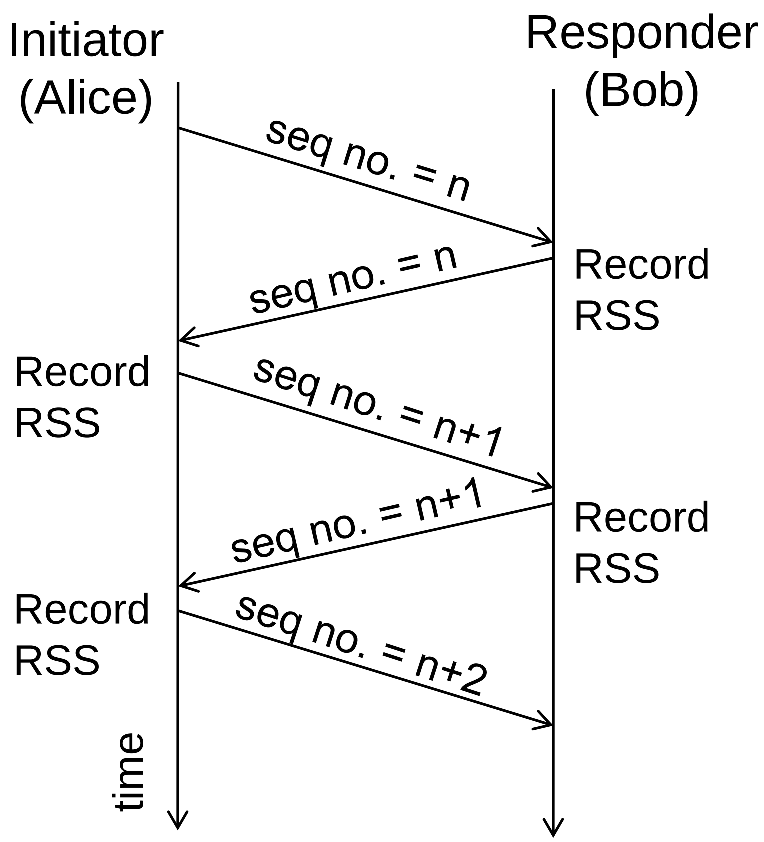
privacy amplification

- 2-universal hash functions
- use *BigNumber OpenSSL* routines

# Implementation



# RSS Measurement Protocol




- packet losses handled by initiator
- 20 ms timeout for detecting packet loss
- responder discards last RSS if duplicate beacon sequence #

# Measurement Goals

- in what kind of settings, key extraction *"works"*?
- how does device heterogeneity affect key extraction?

# Experiments

1. Stationary Endpoints, Intermediate objects

A. Underground concrete tunnel
B. Ed Catmull Gallery
C. Lawn

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2. Mobile Endpoints

D. Walk Indoors
E. Walk Outdoors
F. Bike Ride

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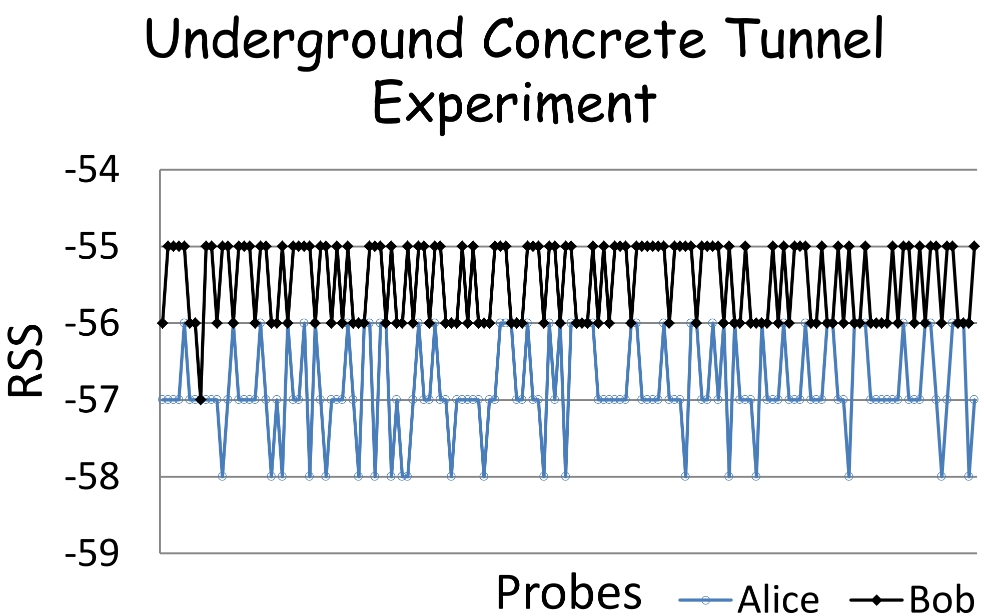
3. Stationary Endpoints, Mobile Intermediate objects

G. Crowded Cafeteria
H. Across busy road

# Stationary Endpoints & Intermediate Objects

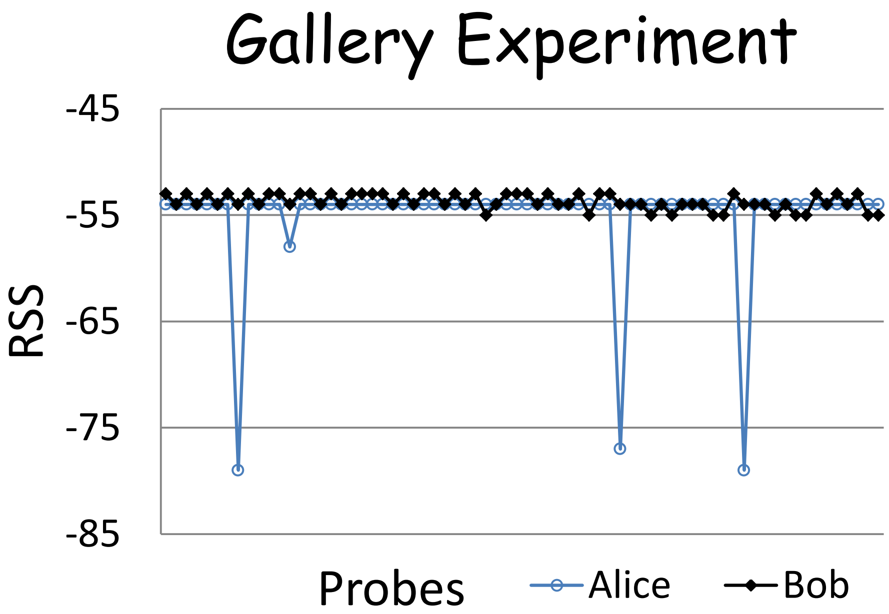



snapshot of data collected for few seconds

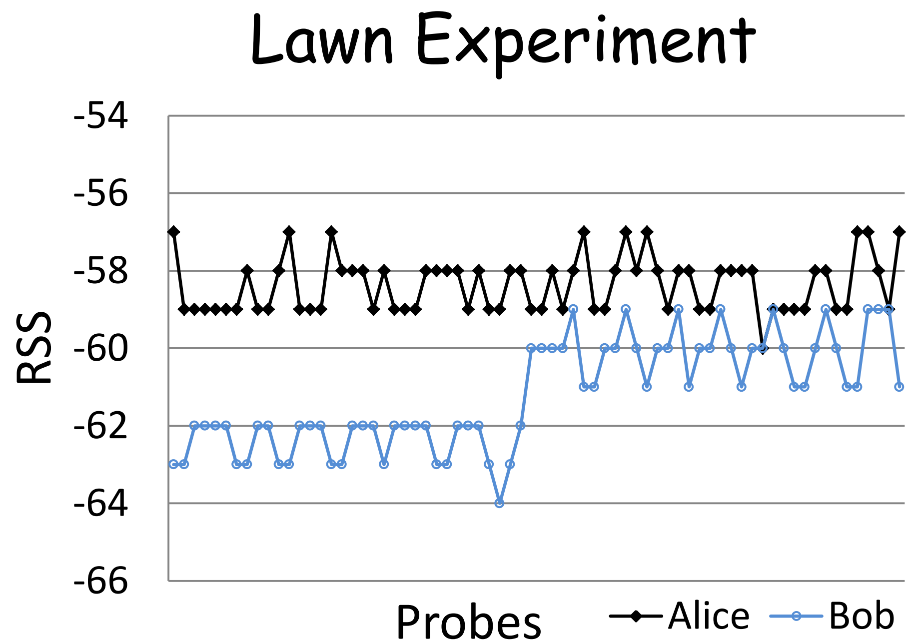
distance between Alice, Bob = 10 feet

- variations very small (range: ~2 dB), exhibit poor reciprocity
- expect Alice's & Bob's bit streams to have very high mismatch
- small scale variations represent noise

# Stationary Endpoints & Intermediate Objects



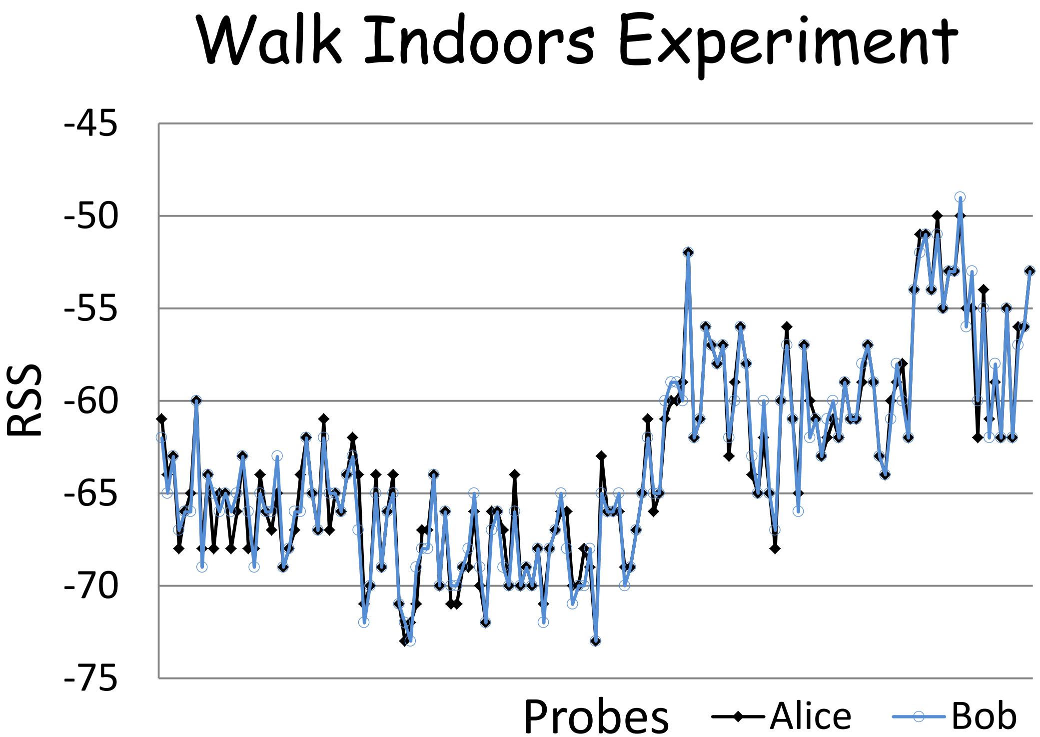

distance = 30 ft




distance = 10 ft

- even typical stationary settings are no different from underground concrete tunnel!

# Mobile Endpoints



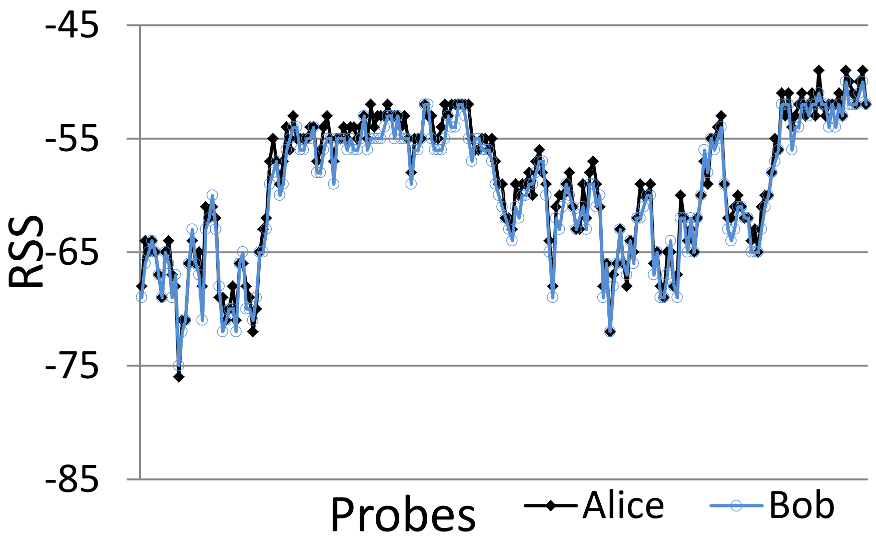

normal walk speed

distance = 10-15 ft

- large variations
  - range ~25 dB
  - highly reciprocal
- hints that Alice's & Bob's bit streams will have very low mismatch

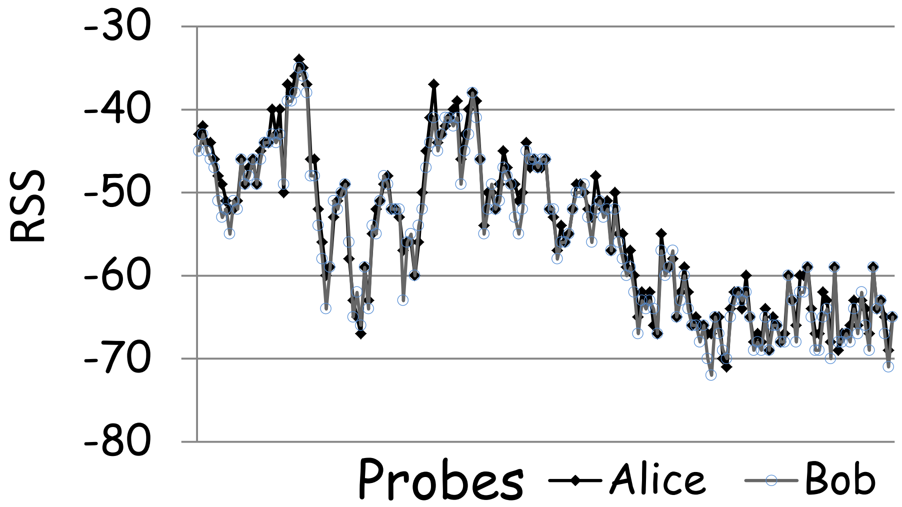
# Mobile Endpoints

Walk Outdoors Experiment




normal walk speed
20-25 ft distance

Bike Ride Experiment

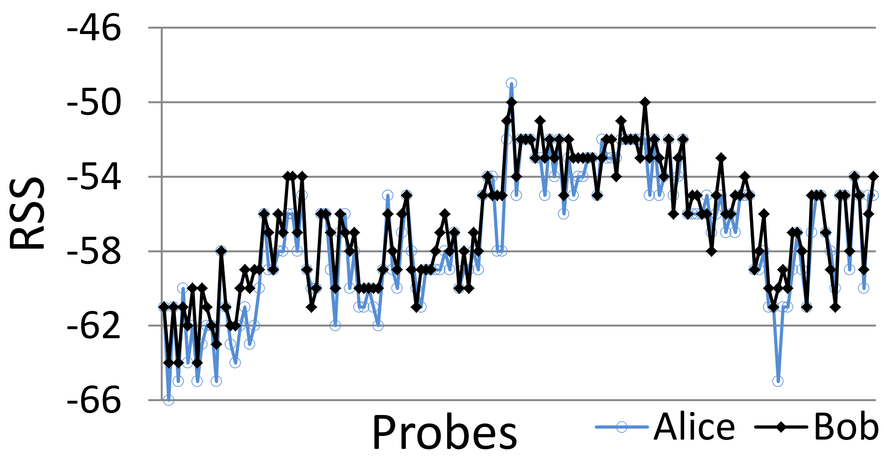



slow bike ride
10 ft or more distance

- more evidence - mobile devices likely to have very low mismatch
- effects of noise diminished by large scale variations

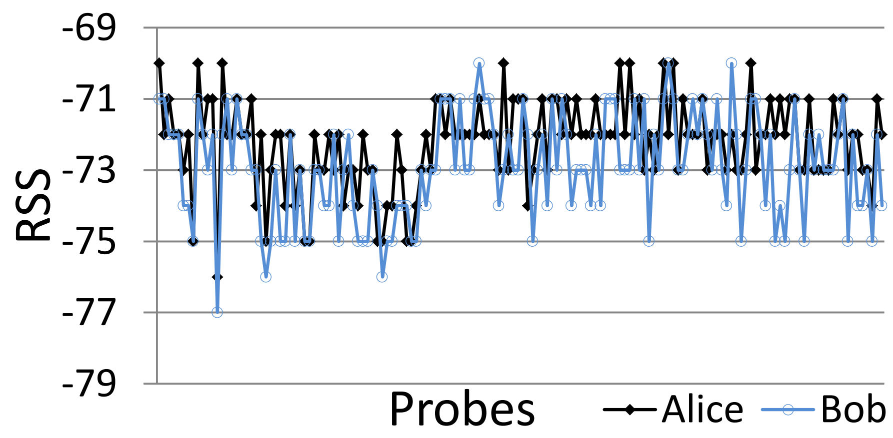
# Mobile Intermediate Objects & Stationary Endpoints

Crowded Cafeteria Experiment




low speed mobility; distance = 10 ft

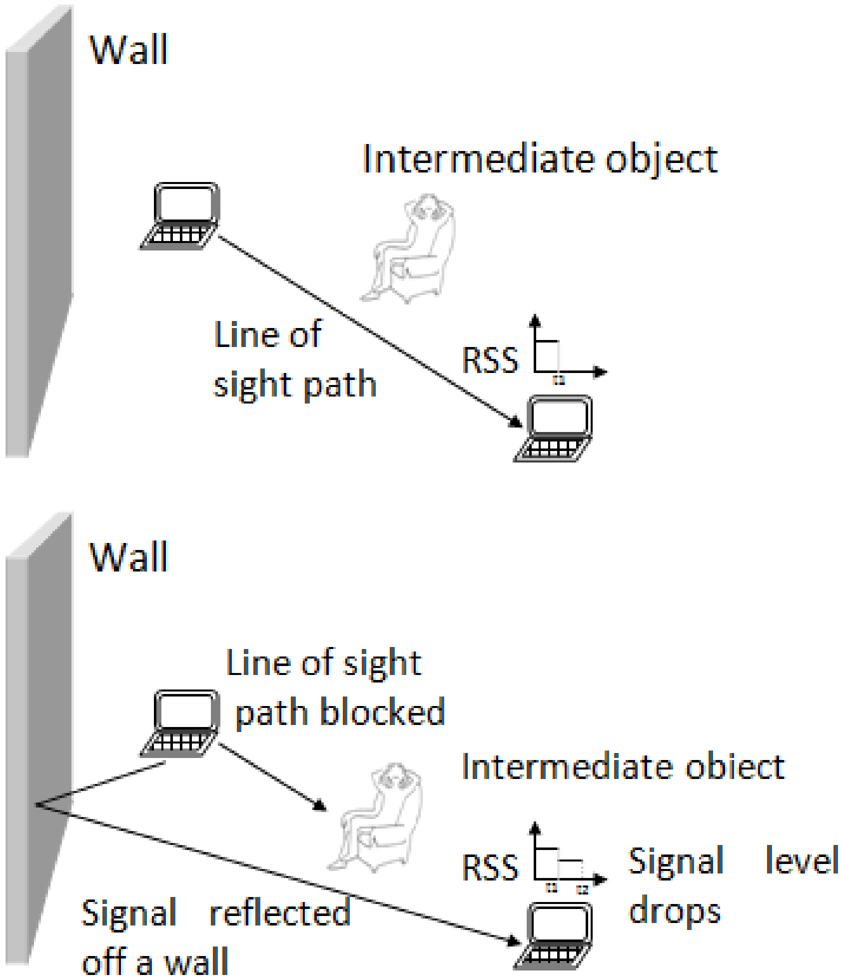
Experiment Across Busy Road




high speed mobility; distance = 25 ft

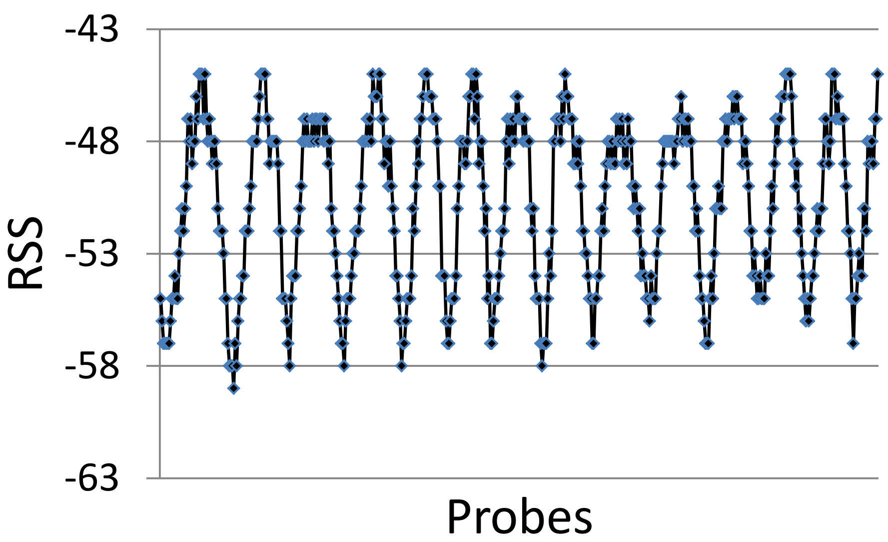
- intermediate variation range (~8-16 dB), reciprocity
- hints - Alice's, Bob's bit streams will have moderate mismatch

# Predictable Channel Attack




- novel attack
- in 'all stationary' settings Eve can cause **predictable channel variations**
  - by controlling movements of intermediate objects
- break key extraction schemes without spending compute power

# Predictable Channel Attack

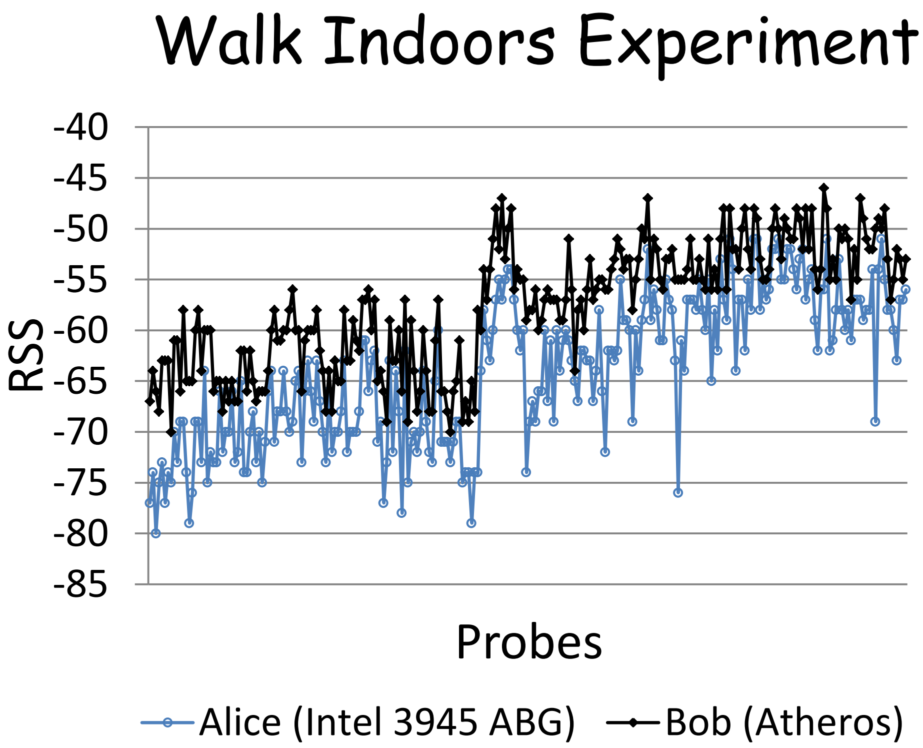



bits extracted:

**0000 1111 0000 1111 …**

- no precision machinery required
- Eve can produce zig-zag patterns, or any other pattern by controlling movements
- no post processing will ensure security of extracted key!

# Effect of Device Heterogeneity



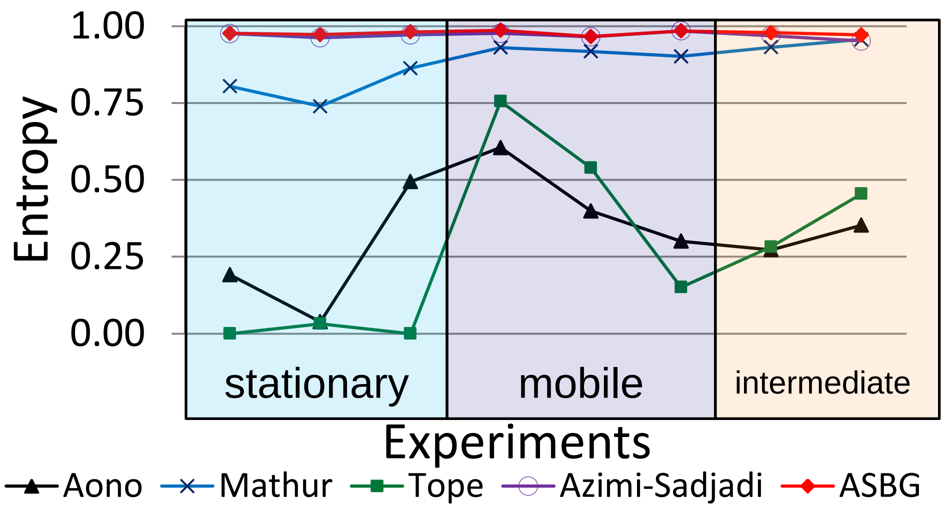

- greater mismatch *than* with homogeneous devices
- mismatch low enough to help establish secret key

# Comparison of Key Extraction Approaches in Various Settings

- performance metrics
  - entropy rate
  - mismatch rate
  - secret bit rate

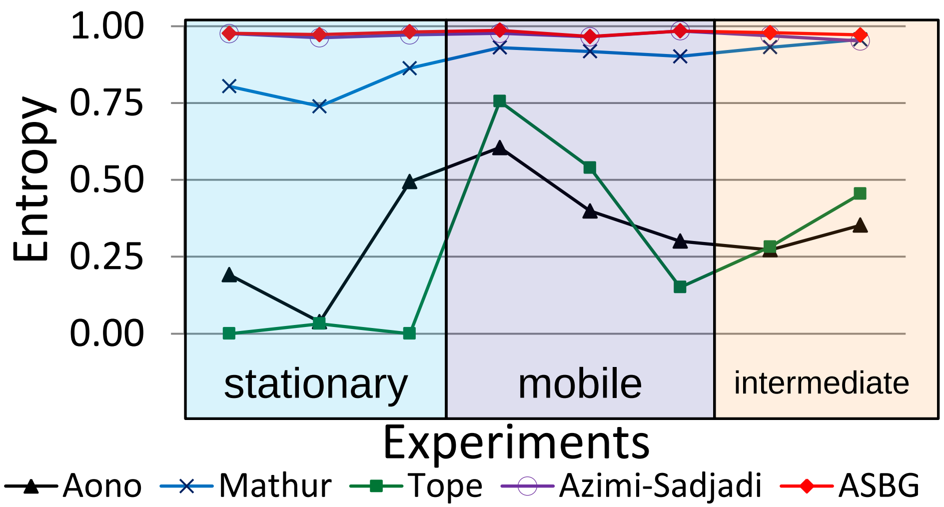
- single bit, multiple bit extraction

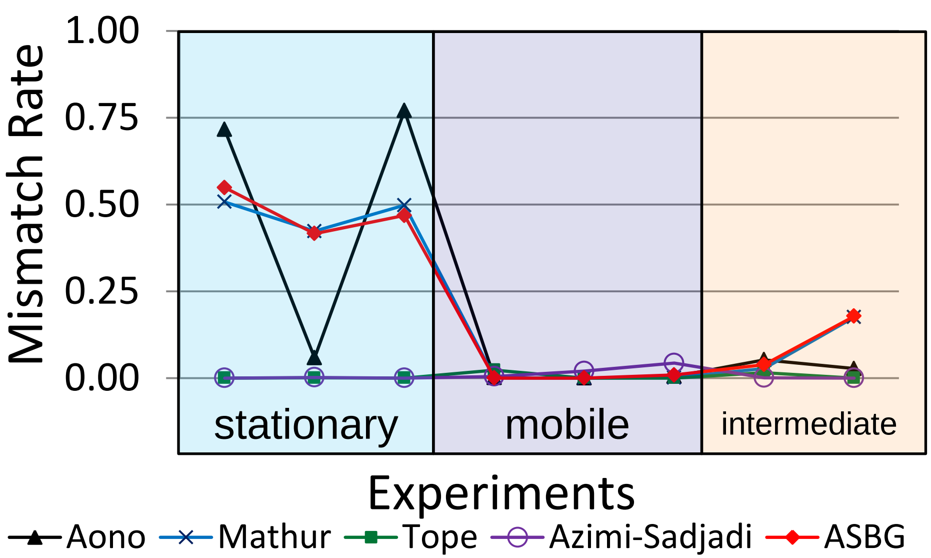
# Comparison of Key Extraction Approaches in various Settings




- secret bit stream from ASBG
  - entropy close to 1
  - passes randomness tests of NIST test suite we conduct

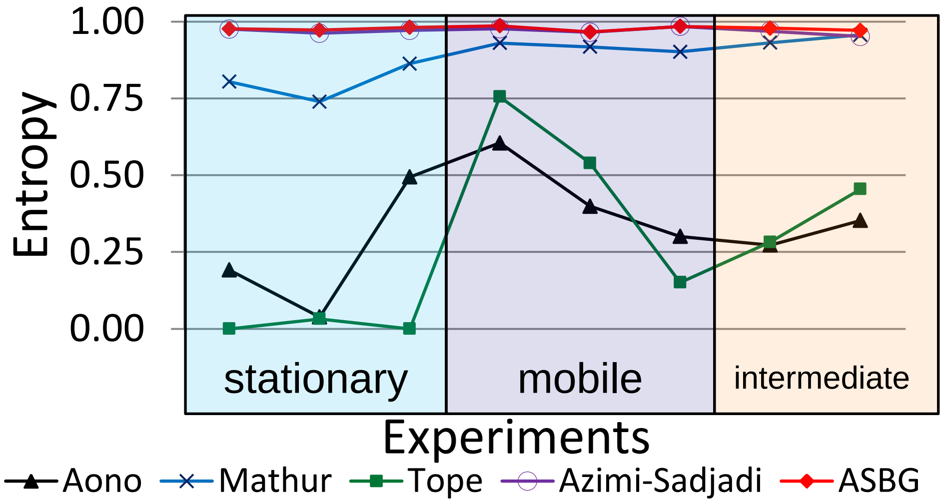
# Comparison of Key Extraction Approaches in various Settings

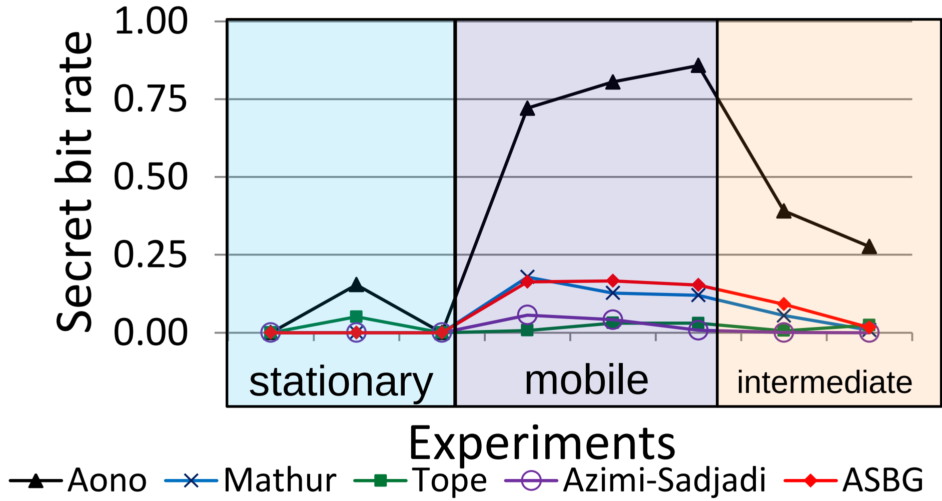


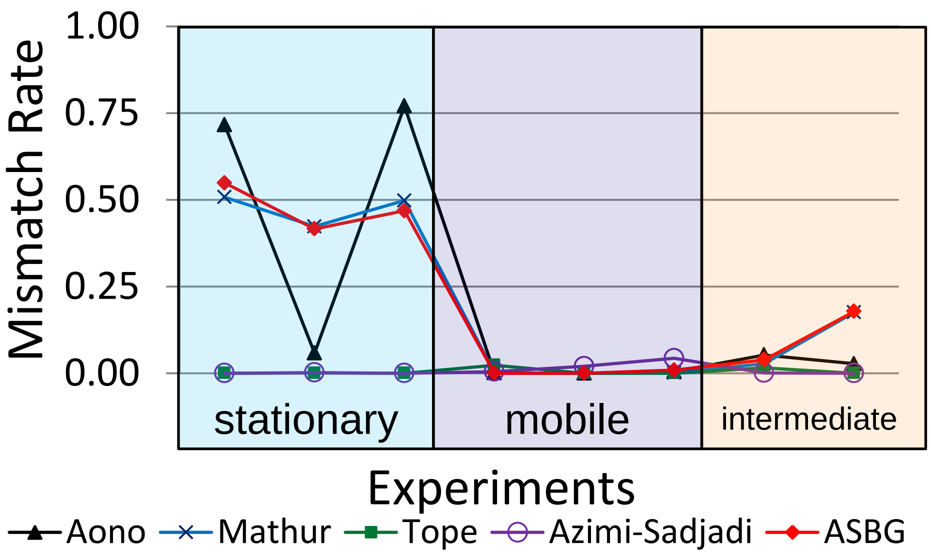




- mobile settings yield bits with low mismatch rates

# Comparison of Key Extraction Approaches in various Settings

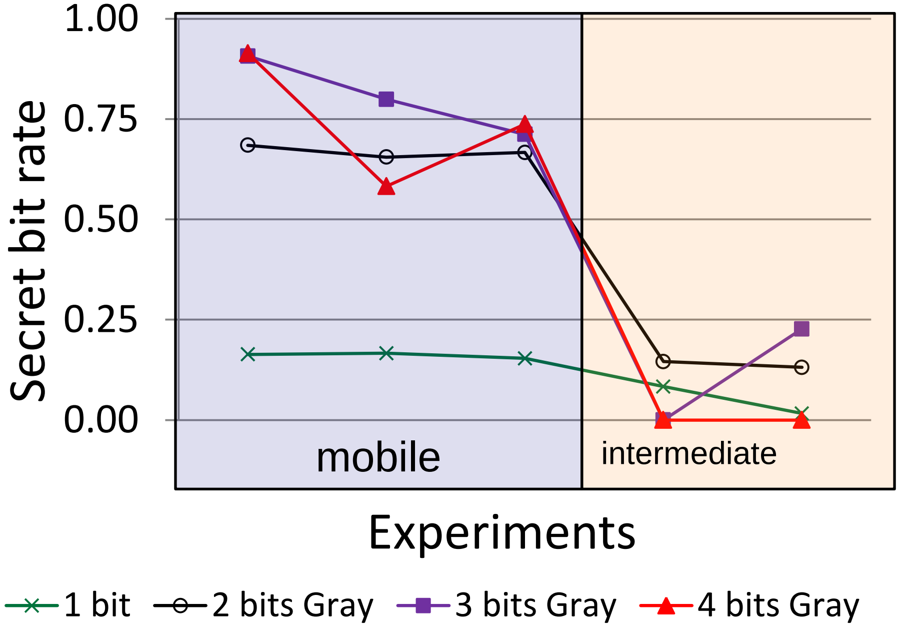


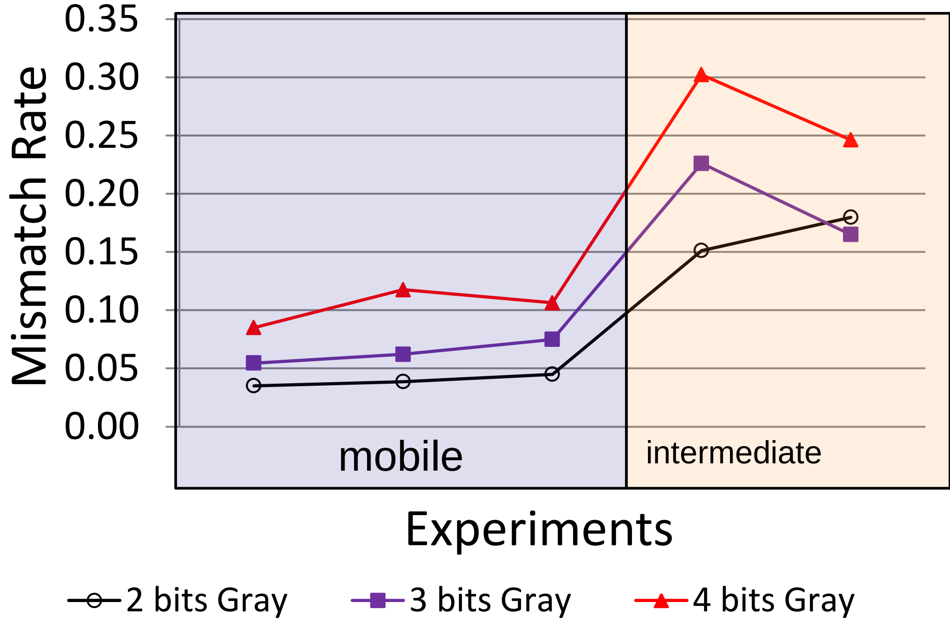




- ASBG exhibits highest secret bit rate among those with entropy > 0.7

# Multiple Bit Extraction




- significant increase in secret bit rate
  - at least 4 times (with N = 2) compared to single bit extraction
- bit mismatch rate increases with N
- Gray code assignment produces smaller mismatch rates

# Summary

- mobile settings best suited for key extraction due to low mismatch
- don't depend solely on movements of limited intermediate objects
  - beware of predictable channel attack!
- our environment adaptive quantization scheme + information reconciliation + privacy amplification generates high entropy bits at high rate