Et Tu Alexa? When Commodity WiFi Devices Turn into Adversarial Motion Sensors

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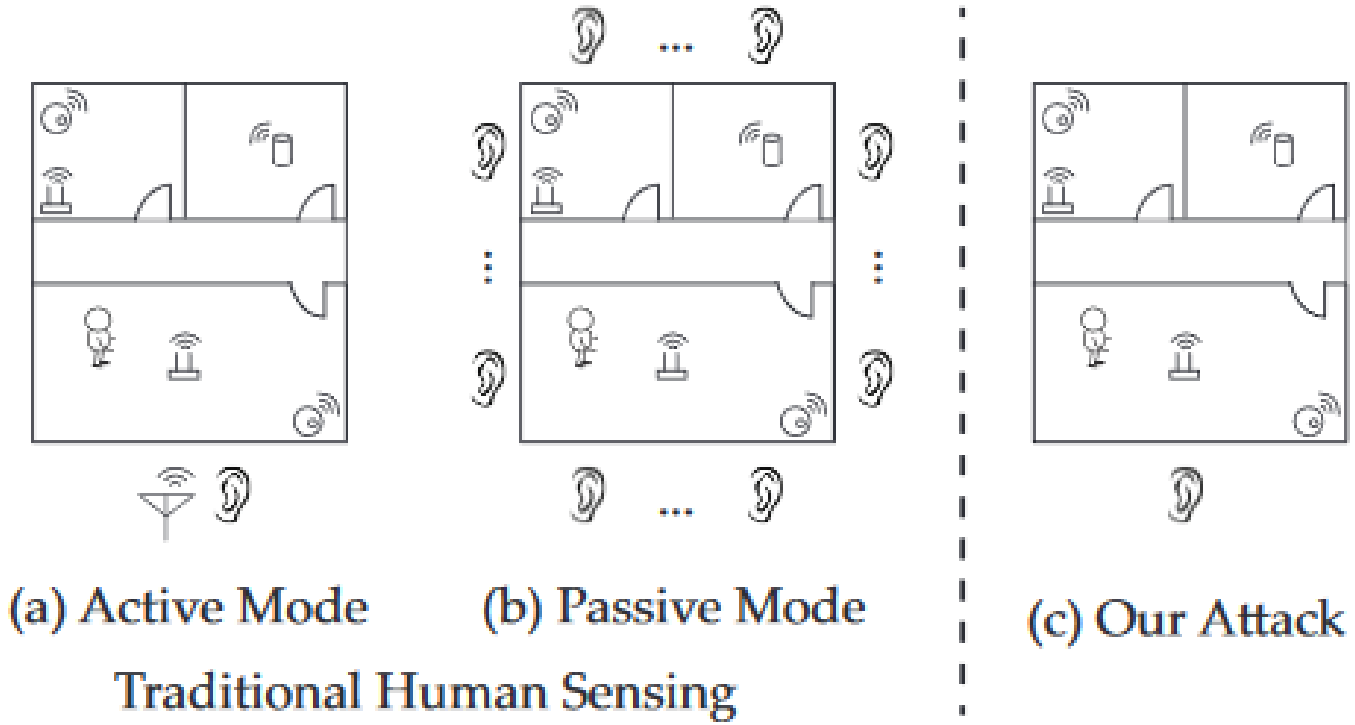


All they use the signals to detect user location

Background Work

- **Active sensing** work (Device continuously transmits RF signals):
  - Most works appear on this area
  - Signals get reflected off the target body,
    - They are captured by the sensing device to infer the target status
  - Since the attacker device must continuously transmit signals, it is easy to detect
- **Passive sensing** work (Devices only listen and do not transmit signals):
  - Multiple sniffers that listen to WiFi signals sent by multiple transmitters in the target area
  - A mechanism to detect the presence of a user when he disturbs the direct path between a WiFi AP and a sniffer
    - The attacker must obtain AP locations a priori and deploy multiple sniffers around the target area

Motivation

- There are human sensing systems that can be turned into attacks but they impose a hefty cost and risk for the attacks
  - This limits the applicability of the attack
- Can we simply reuse existing work on device-free human sensing systems to launch adversarial sensing attacks?
- Can we find a passive human sensing attack that can be launched by a minimally equipped attacker and remain undetected?

Contribution

- A silent attack that continuously detect, monitor/locate human motion behind walls
  - Uses a novel model on multipath signal dynamics to remove dependences on active transmissions
  - Remain undetectable
  - Low cost (cheap commodity hardware). ONLY a single WiFi receiver (with a single antenna)
  - No need to compromise devices or decode/decrypt the network traffic
- The attack was validated in real-world settings.
- A practical and effective defense using AP-based obfuscation

WiFi signal propagation

- 1) User movement near a WiFi transmitter changes its signal propagation in a way that can be observed by nearby receivers
- 2) Walls and buildings today are not built insulated against WiFi signals
  - Signals sent by devices inside a property can often be overheard by outside receivers

Motion Detection via multipath signal dynamics

- The model links together
  - Human motion near WiFi transmitters
  - Variances of multipath signal propagation seen by a sniffer outside of the property
- When a human moves near a WiFi device ***x***, the motion changes the multipath signal propagation to the attacker sniffer ***S***.
  - This model allows S to capture such signal dynamics and use them to pinpoint the target to a specific location
- OF COURSE: The more WiFi devices inside the property, the more accurate tracking

Assumptions

- No knowledge about the WiFi network and the devices inside the property (including their locations)
- At least one WiFi device inside a room is needed for the attack to be effective
  - In case of relocating a sensor, the attack still works as accurate as before

Limitations

- The model is unable to identify features like: speed, activity type and user identity or separate humans from large animals.
- A passive sniffer with a single antenna cannot extract advanced signal features including phase of CSI, Time of Flight (ToF), Angle of Arrival (AoA) etc.

Attack Scenario

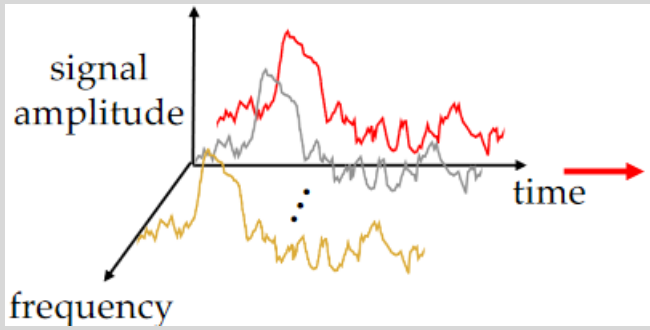
- **One sniffer and many anchors**
  - The attack leverages the ubiquity of commodity WiFi devices (e.g. routers, printers)
    - These devices are often spread over each room of a home and office
    - These WiFi devices will be referred as **anchors** in this presentation
  - The attack leverages the fact that WiFi signals are designed for significant coverage and can penetrate most walls
    - Attackers can place a sniffer outside the target property to passively listen to signals
  - Recall: WiFi protocols do not encrypt source/destination MAC addresses
    - Thus, the sniffer can isolate packets sent by each other

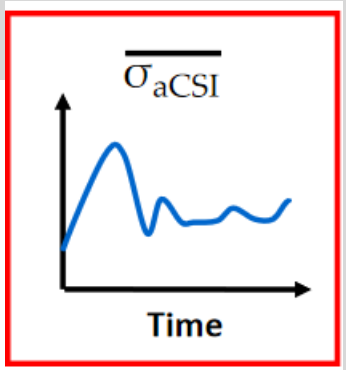
Adversarial Model

- Adversary **makes no assumptions** about the number, location or movement speed of human targets being tracked
- He **does not have physical access** to WiFi devices in the target property
- He **can physically move *outside* the target property**, either outside exterior walls or along public corridors without attracting suspicion
- To avoid detection, **he** only **performs passive WiFi sniffing**, without any specialized hardware. He needs a sniffer that has only a single built-in antenna
- He **divides the target property into "regions"** around the anchors to detect user presence.

Measuring Signal Variation via CSI

- This attack leverage the **Channel State Information (CSI)**, which captures the signal strength under different carriers
- To measure the variation, first gather the raw value of CSI
- Compute the standard deviation for each sub-frequency
- Average those standard deviations across different sub-frequencies
- Result: The average $\overline{\sigma_{aCSI}}$

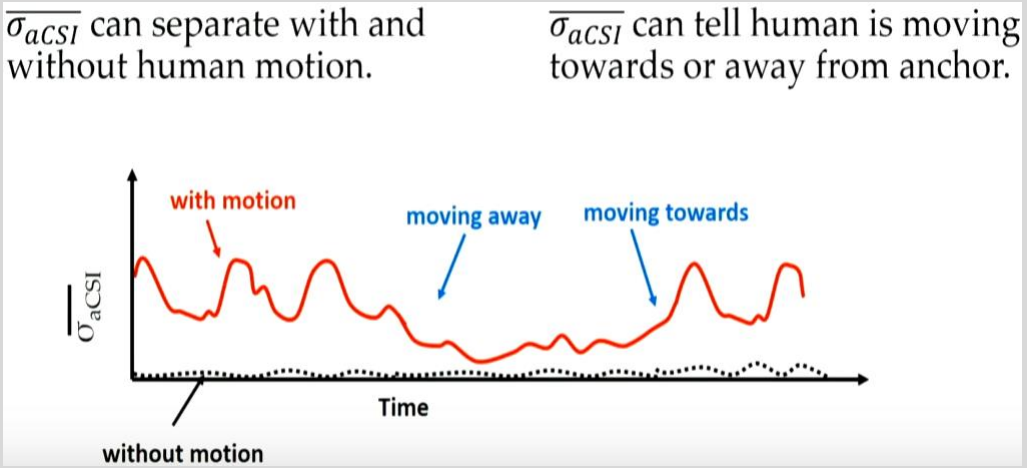




Our final metric

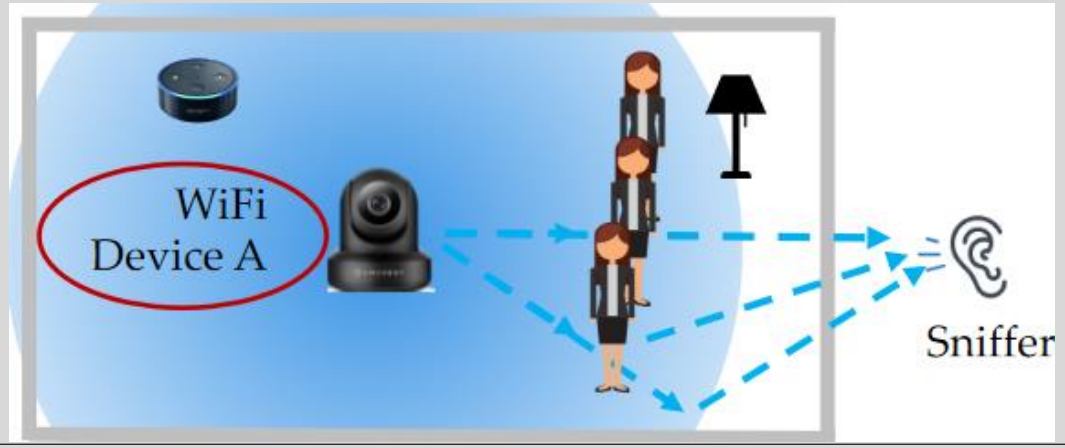
Observations (1)

- **User movement → aCSI variance**
  - Humans are never completely stationary (e.g., playing games, walking)
    - Their natural movements will disturb the multipath signal propagation of nearby WiFi transmitters (i.e. anchors), creating variations in their aCSI values seen by the sniffer

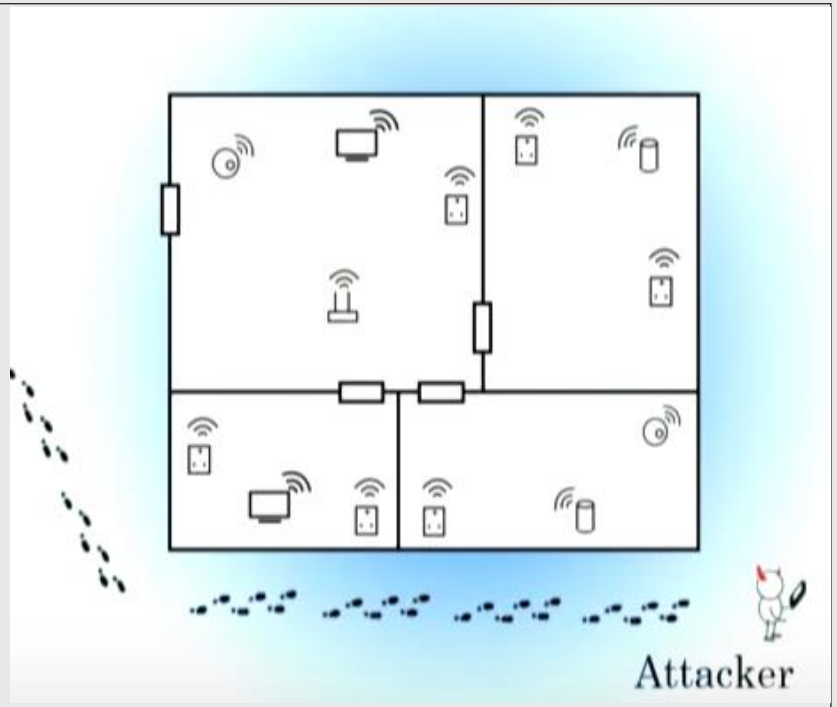


Observations (2)

- As a target moves in the space between an anchor **x** and the sniffer, it blocks and diffracts some signal paths from **x** to the sniffer.
- When close to **x**, it affects more paths than when it is far away from **x**
- Thus, the received signals seen by the sniffer will display a larger temporal variation when the user is closer

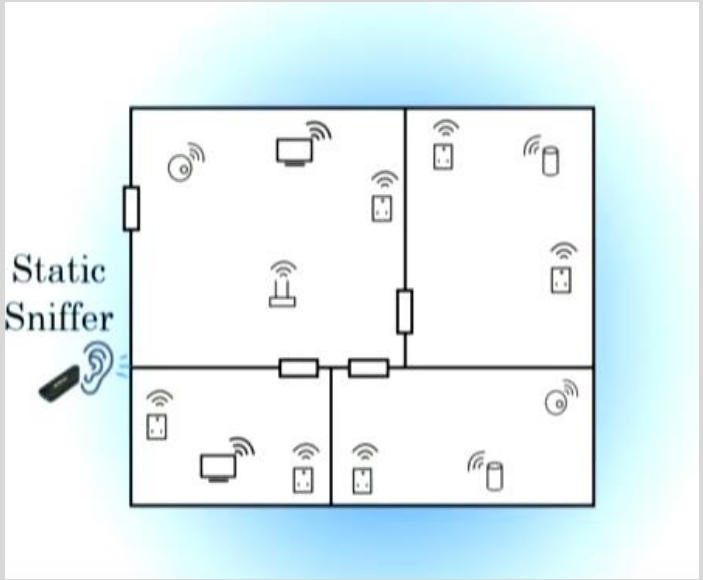


Attack Design (1)



- **Two steps:**
  - **Bootstrapping,**
  - **Continuous monitoring**
- **Identify and locate anchors during "bootstrapping"**
  - The attacker needs to **identify** and **locate** the anchors in the target area.
    - The **unique feature of our motion detection** is that is does not require precise location of anchors, only their individual room.
  - This is achieved by the attacker **performing** a brief **passive WiFi measurement** while walking outside the target property.

Attack Design (2)



- **Deploy the sniffer and perform "continuous human sensing."**
  - The **attacker hides the** same **sniffer** at a fixed location outside the target area.
  - The **sniffer continuously monitors WiFi signals**, and uses them to locate human presence.
  - The **sniffer monitors each detected anchor**, and any relocation of an anchor will trigger its removal from the anchor list,
    - We need another bootstrapping phase to (re)locate the anchors

Evaluation (1)

- **Experiments**
  - 11 homes & offices with various floorplans
  - 31 WiFi devices
    - These devices are naturally placed at locations where they are designed to be
  - A static sniffer outside of the target building within 2m to the target
  - Modified the WiFi firmware to passively collect CSI
  - The volunteers are aware of the attack goals but not the techniques

Evaluation (2)

- Having more anchors increases the chance that a user movement triggers at least one anchor.

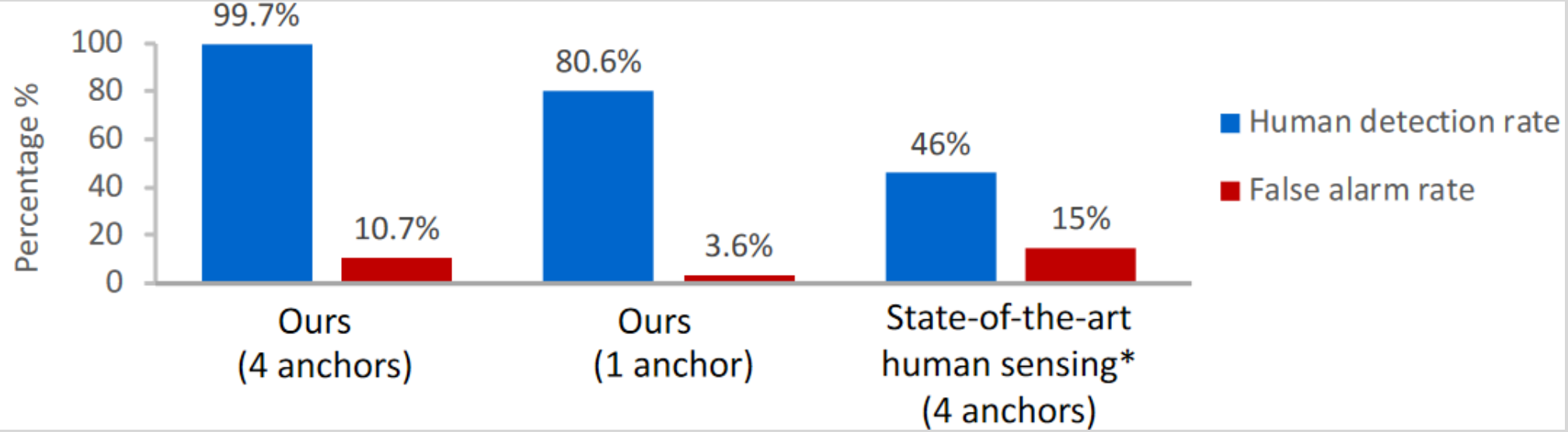
- **Detection rate(DR)** measures the probability of the attack reporting a room as being occupied when it is actually occupied, across all the slots.
- **False positive rate(FP)** measures the probability of a room not being occupied when our attack reports that it is being occupied.

$$\text{Human detection rate} = \frac{\text{T(attacker reports room has human inside)}}{\text{T(room has human inside)}}$$

$$\text{False alarm rate} = \frac{\text{T(room does not have human inside)}}{\text{T(attacker reports room has human inside)}}$$

Is the attack effective?

- **LiFS** requires each anchor's precise physical location in the room (which is not available to our attacker), we use the room center as the input to **LiFS**, mapping to 1–2m localization error.
  - LiFS also requires knowledge of the aCSI value when no user is present,



*** LiFS: Low human-effort, device-free localization with fine-grained subcarrier information. MobiCom'16.**

Is the attack robust?

- How effective is the attack at low-rate packet?
  - Human detection **drops only 1.5%** when anchors transmits at 2 packets per second, compared to full rate 11pps
- How about non-human sources motions?
  - **Human motion differs from equipment motion** commonly seen in homes (e.g.an oscillating fan and a robot vacuum).
    - The latter either is **too weak to produce any notable impact** on aCSI or generates periodic signal patterns different from those of human motion

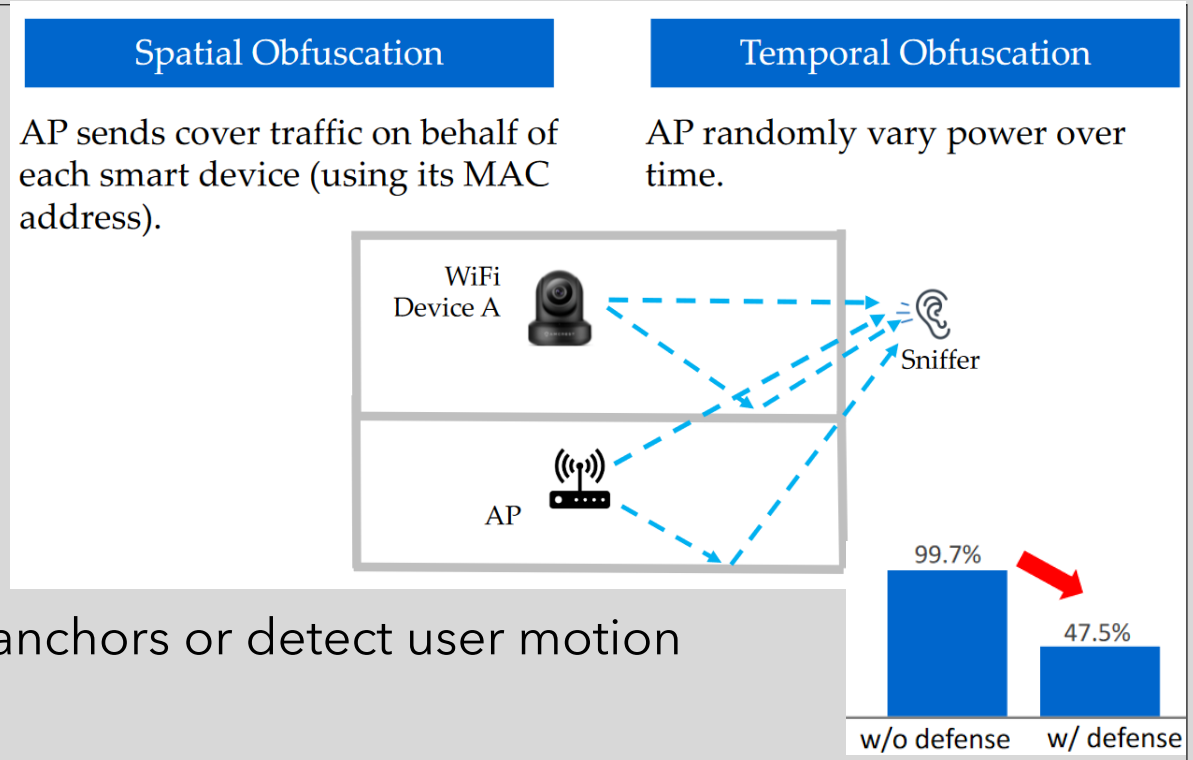
Existing Defenses (1)

- The **effectiveness of the attack depends** heavily on the **quantity** and **quality** of the WiFi signals captured by the sniffer
- **MAC Randomization**
  - Since the attack sniffer uses MAC address to isolate signals of anchors, MAC randomization can disrupt both bootstrapping and continuous sensing phases
    - This featured **is disabled on most devices** (according to recent work)
    - Android 9.0 switches to per-network MAC randomization, which does not apply any MAC randomization to static WiFi devices

Existing Defenses (2)

- **Geofencing**
  - Bounds signal propagation to reduce WiFi signals accessible to the adversary
  - Geofencing is also difficult to deploy and configure:
    - Reduce the anchor's transmit power, which is almost always undesirable since it degrades connectivity.
    - Equip WiFi devices with directional antennas, limiting signal spatial coverage.
      - Higher cost and larger form factor
- **WiFi rate limiting**
  - Is undesirable for most network applications. Many **WiFi devices, when idle, transmit at more than 2pps**. It is hard to rate limit further, rendering the defense ineffective.

Proposed Defense (1)



- **Signal obfuscation by AP**
  - Adds noise to WiFi signals
    - Adversaries cannot accurately localize anchors or detect user motion
- **Spatial obfuscation**
  - The **WiFi AP** actively **injects customized cover traffic** for any of its associated WiFi devices **w** that is actively transmitting.
    - This **produces large ambiguity** to the attack
- **Temporal obfuscation**
  - WiFi devices change transmit power randomly over time, injecting artificial noises to signals seen by the sniffer
    - It needs equipment with higher cost/energy consumption

Summary

- **An adversary can accurately detect and track movements of users**
  - **No compromisation** of any device is needed
  - **Only passive WiFi signal analysis**
- It seems to be **effective under real conditions**
- Defense:
  - **AP-based obfuscation** is quite effective

THANK YOU!

Questions?